NCEE
NATIONAL CENTER FOR
ENVIRONMENTAL ECONOMICS

Global Climate Control: Is There a Better Strategy Than Reducing Greenhouse Gas Emissions?

Alan Carlin

Working Paper Series

Working Paper # 06-04
September, 2006

U.S. Environmental Protection Agency
National Center for Environmental Economics
1200 Pennsylvania Avenue, NW (MC 1809)
Washington, DC 20460
http://www.epa.gov/economics

Global Climate Control: Is There a Better Strategy Than Reducing Greenhouse Gas Emissions?

Alan Carlin

Correspondence:

Alan Carlin
1200 Pennsylvania Ave
Mail Code 1809T
Washington, DC 20460
202-566-2250
carlin.alan@epa.gov

NCEE Working Paper Series

Working Paper # 06-04
September, 2006

GLOBAL CLIMATE CONTROL: IS THERE A BETTER STRATEGY THAN REDUCING GREENHOUSE GAS EMISSIONS?

Alan Carlin

Correspondence:
Alan Carlin
Mailcode 1809T
US Environmental Protection Agency
Washington, DC 20460
202-566-2250
carlin.alan@epa.gov

Disclaimer

The author is indebted to Dr. John Davidson of EPA and Dr. Richard Ball of Annandale, VA, for comments on earlier drafts. The views expressed in this paper, however, are those of the author alone- and do not necessarily represent those of the U.S. Environmental Protection Agency. In addition, although the research described in this paper may have been funded entirely or in part by the U.S. Environmental Protection Agency, it has not been subjected to the Agency's required peer and policy review. No official Agency endorsement should be inferred.

GLOBAL CLIMATE CONTROL: IS THERE A BETTER STRATEGY THAN REDUCING GREENHOUSE GAS EMISSIONS?

Alan Carlin

September, 2006

Abstract

Many environmentalists and some developed nations appear to have concluded that there is one
Many environmentalists and some developed nations appear to have concluded that there is one
climate change problem, global warming, and that there is only one solution to it, reducing greenhouse gas emissions, usually through the Kyoto Protocol. This paper argues instead that there are actually four major inter-related problems and concludes that several different approaches, including engineered climate selection, would be required to solve all of them. Although some measures can address certain climate change problems, none can address all of them. The paper first reviews the four major climate change problems, analyses whether the most prominent of the greenhouse gas control approaches (the Kyoto Protocol) is likely to be either effective or efficient in solving them, and then analyses both management and technological alternatives to this approach.

The paper concludes that the most efficient and effective approach would be to actively pursue both engineered climate selection approaches involving radiative forcing using stratospheric particles optimized for this purpose as well as a new effort to reduce ocean acidification, with immediate priority given to the former in order to solve all the non-ocean acidification problems quickly while the more difficult, much slower, and much more costly effort to reduce ocean acidification is analyzed and carried out. This two-fold approach could be used to rapidly reduce the risks from adverse feedback/tipping point problems from global warming and from global cooling from major volcanic eruptions, and to rapidly stabilize average global temperatures at any desired level. This should also allow a little time for a new effort to better understand ocean acidification and design and carry out a careful program to reduce it directly, or possibly to decrease the carbon dioxide levels themselves to the extent that this is the most effective and lowest cost approach. If the latter, this should result in the lowest possible costs of carbon dioxide control by stretching out the period in which they would be made given the sensitivity of the costs of carbon dioxide emissions reductions to the rapidity with which they occur.

Keywords: Global warming control, global climate change control, cost-benefit analysis, cost-effectiveness analysis

Subject areas: Climate change, environmental policy, benefit-cost analysis

Contents:

1. Introduction

Humans have embarked on an inadvertent and very risky experiment involving rapidly increasing greenhouse gas (GHG) levels in the atmosphere. The question examined here is not whether the experiment is taking place but rather whether there are efficient and effective remedies for the problems that appear likely to result. Because of the extreme complexity of the problem and the number of disciplines that need to be involved in defining a practical solution, the analysis must necessarily be equally complicated and broadly based. Unfortunately, many previous analyses have ignored the fact that any remedies adopted must not only be technically sound but also economically and politically feasible. Although the emphasis here will be on economics, a serious attempt has been made to factor in all the other factors that need to be taken into account to find a workable solution to what is probably the most difficult environmental problem that modern humans have faced.

One of the greatest difficulties in solving the climate change problems results from the fact that no one has really leveled with the public as to how difficult it would be to achieve the goals that the advocates believe are necessary. This may entice the public to embrace particular solutions to the problem, but in the longer run spells major problems for implementing them as it becomes clearer to everyone what is really involved. It seems better to outline the full difficulties involved and then attempt to find the best available solutions.

This paper was inspired in part by a call for wide-ranging, objective analysis of available technological options to solve climate change problems made by Allenby (2003) in a recent report from the National Academy of Engineering:

> The current approach to global climate change carries within it not just policies, but also a vision, a teleology of the world that is, in important ways, both unexpressed and exclusionary…. Perhaps for this reason, the role of technology has been relatively ignored throughout the negotiating process and, when it has come up, has been quickly marginalized.
>
> In fact, there are many possible technologies that might reduce carbon loading in the atmosphere, but many of the most important ones are out of favor. For example, nuclear energy has been excluded by general agreement, and geoengineering (e.g., aluminum balloons in the stratosphere to reduce incoming energy to the atmosphere) has been shunted aside, regarded as the dream of a few eccentrics (Keith, 2000). Biotechnology to improve agricultural efficiency and biological carbon sequestration are clearly not acceptable to many participants in the Kyoto process, and to many environmentalists generally. The rejection of these and other technologies tends to reinforce the impression that the Kyoto process is an exercise in social engineering by Europe targeted at the United States. Regardless of the truth, this impression is obviously conducive to conflict and deadlock (as indeed has happened)….
>
> A useful process that would contribute significantly to the rational, ethical management of the future would be to categorize technological possibilities and determine, as objectively as we can, their risks and benefits and the optimal scale for each. We could then develop a portfolio of options for future negotiations. Technology, especially in emotionally and ideologically charged environmental debates, almost never provides complete answers. But an array of technological options enables choice and thus increases

> the chances that we will be able to balance the disparate values, ethics, and design objectives and constraints implicit in the climate change discourse. Technology may help us respond to the world we are creating in responsible, ethical, and rational ways.

Some other prominent scientists have recently voiced similar thoughts.[1]

This paper first defines four major climate change problems, then analyses whether the most prominent of the greenhouse gas control approaches is likely to be either effective or efficient, and then analyses some management and technological alternatives to it.

The standard response to most pollution problems has been to impose regulations limiting the production and/or discharge of the pollutants involved, in this case greenhouse gases (GHGs). Economists have suggested that a more economically efficient approach would be to provide economic incentives to reduce discharges. This regulatory approach has been the basis for most of the discussions of global warming as well, and underlies the major current effort represented by the Kyoto Protocol. This pollutant mitigation approach to global warming assumes that if somehow human-induced pollution (in this case of GHGs) could be reduced/eliminated, then Earth's climate change problems would be solved. The available evidence, however, suggests that this underlying assumption is incorrect and that the current Kyoto approach is highly unlikely to return greenhouse gas (GHG) emissions to pre-human levels anyway.

This paper assumes that recent predictions as to the effects of greenhouse gas emissions on climate are broadly correct and will not discuss the reasons for believing that warming is or is not currently going on. Rather, the purpose of this paper is to ask what the climate change problems are, whether the Kyoto Protocol approach is the most useful tool for solving them, and what approaches might be more efficient and effective.

This paper takes a broad view of the problem not only by looking at a broad range of climate change problems and the management and technological options for their solution, such as Allenby suggests, but also by viewing climate change in the larger context of both short and long-term effects of natural forces and human activities on climate. Climate history is considered over the last three million years since the beginning of the current chapter in Earth history rather than the last hundred years or even the current Holocene Epoch, which is the focus of most discussions on climate policy.

1.1 Needed Characteristics of Approaches Used to Control Climate Change

Except for the addition of a seventh and an eighth criteria, the criteria proposed in this section are very similar to those found in Alby et al. (2003), so substantial added justification and detail concerning the first six criteria can be found there with the exception that criterion 5 has been made much more specific because of the broader perspective taken in this paper of the range of climate change situations that may require attention. The seventh criteria may be captured by criteria 2 and 3 since such risks have economic costs, but since these risks are usually poorly understood and therefore very difficult to quantify, it appears better to make this an added criterion. The eighth is an "other" category needed for a more general comparison of the remedies.

1. *Effective environmental outcome*—Will implementing the management tool/remedy result in the desired climate management in a timely manner? Remedies that are not effective can be worse than no remedy since people may believe that a problem is being solved when it is not.

2. *Economic feasibility*—Will implementing the management tool/remedy produce positive net economic benefits? Remedies that do not will decrease overall human economic welfare.
3. *Cost-effectiveness*; specifically, 3a. Cost of control—In the case of global average temperature change, what is the cost-effectiveness of the management tool/remedy in terms (ideally) of its long-term marginal costs expressed in dollars per ton carbon of CO_2 emissions mitigated? All other things equal, remedies that can achieve a given goal (in this case a given level of CO_2 emissions) at lower cost are preferable to those that achieve them at a higher cost. Marginal costs measure the cost of the last and presumably most expensive project that would be undertaken using a given remedy and facilitate comparisons with the alternatives and with estimates of the economic benefits to be achieved. Where there is little variation between the cost of projects per unit of emissions reduction, this distinction is of little importance. But where there is a broad range, this is of importance. Obviously there are also opportunities for controlling other GHG emissions, but it is assumed here that CO_2 emissions control is broadly representative of those available for other GHG emissions in terms of the broad remedies/tools available for doing so.
4. *Improved distributional equity*—What is the impact of the management tool/remedy in terms of its impact on various human income groups/nations? Remedies that improve distributional equity would appear to be preferable to those that do not.
5. *Provide policy flexibility*—If conditions change, how easily and how rapidly can the management tool/remedy being pursued be changed to meet the new conditions? Because natural climate changes may occur abruptly, particularly during periods of climate transition and major volcanic eruptions, and because of the substantial scientific uncertainties involved, a static approach that is difficult to change in relatively short time frames will be much less useful than more flexible ones. There are at least three important aspects of flexibility in the context of climate change. The first (5a) is the ability to alter the pace of implementation of a remedy being considered as needed to meet changing conditions. The second (5b) is the capability to deal with global cooling as well as global warming if conditions change or a major volcanic eruption results in rapid cooling. A third aspect (5c) is the ability to deal with global temperature distribution. As discussed in Section 2, global warming and to some extent cooling represent real risks for Spaceship Earth and its living cargo. Given the reality of long lead times for changing the atmospheric levels for GHGs and given the less than overwhelming correlation between these levels and global temperatures, it would appear that a faster-acting, more effective, lower cost, and quickly reversible approach is much to be preferred in any attempt to influence global temperatures.
6. *Not place undue demands on participation and compliance*—Does the management tool/remedy require widespread active participation and compliance to be successful? How likely is that to occur? Greater such demands reduce the likelihood of successful implementation of a management tool/remedy.
7. *Not pose other major environmental risks or provide other environmental benefits*—Does the management tool/remedy create other environmental risks unrelated to climate control? If the remedy poses a significant risk of creating other environmental risks, the world may not be better off as a result of using it. Or are there other environmental benefits?

8. *Have other important favorable characteristics/lack other problems*—Are there other important advantages/drawbacks to the proposed management tool/remedy not already discussed?

1.2 What Are the Problems?

Although the problems posed by climate change are often considered to be a single problem (usually referred to as global warming) with a single solution (reducing greenhouse gas emissions through implementing the Kyoto Protocol), they can more usefully be viewed as four interrelated problems (shown in Table 1) that have both human and natural origins since the effects of and solutions to these problems are significantly different. The four are:

(P1) The general trend of global temperatures is currently a gradual increase and this appears likely to continue for the foreseeable future (see Section 2 for further discussion). This gives rise to a number of identifiable adverse effects, including sea level rise, arctic thawing, and possibly increased hurricane strength, among others.

(P2) Changes in atmospheric levels of GHGs have other non-temperature-related effects. In some cases these are believed to be quite positive, but at least one of them, ocean acidification, appears to have important adverse effects. A more detailed discussion can be found in Section 5.3 below.

(P3) There is an increasing risk that climate changes will trigger various "tipping points," where some believe that there will be particularly adverse feedbacks or other abrupt climate changes from continued global warming. There may also be other natural events that will result in abrupt climate changes as well. A brief discussion of the scientific aspects of these effects can be found in Section 2.8 below.

(P4) There will almost certainly be shorter-term episodes of global cooling resulting from major volcanic eruptions and possibly other natural causes. In the 20th Century, such eruptions occurred on average about once a decade and had significant but not overwhelming adverse effects. In the extreme case, however, a few of these episodes have in the past and are likely at some point in the future to be catastrophic to humans and to much of life on Earth. A brief discussion of the scientific aspects of these effects can be found in Section 2.8 below.

It is important to emphasize that the risks posed by each of these problems are different in magnitude, timing, and likelihood, so they are not directly comparable with each other. But they all impose risks and have potential adverse effects.

1.3 What Are the Solutions?

One of the primary purposes of this paper is to examine some of the major available remedies/approaches/tools for climate control using the criteria discussed in Section 1.1. These approaches can be divided into two general types: management and technological. In a number of ways these two approaches are parallel and either one could be used. In an attempt to simplify this confusing situation, however, this paper combines the two approaches primarily on the basis of the management approaches (MAs) but with some aspects of the technological approaches (TAs).

1.3.1 Management Approaches

There would appear to be at least four general approaches as to how humans could "manage" these problems with several sub-scenarios based on different assumptions as to the management approaches used:

- (MA1) Non-stabilized "business-as-usual" carbonization and adaptation
- (MA2) Currently debated de-carbonization
  - (MA2a) Kyoto and possible follow-ons
  - (MA2b) Decentralized
  - (MA2c) Liability-based
- (MA3) Engineered climate selection
- (MA4) International approach including use of all available technologies

(MA1) Non-stabilized "Business-as-usual" Carbonization and Adaptation

This management approach assumes that fossil fuel use and GHG releases continue roughly as they have been doing in recent decades in countries other than the participating Annex I nations in the Kyoto Protocol. This means that atmospheric levels of CO_2 would continue to increase at roughly 2-3 ppmv per year. This approach corresponds to remedy A in Sections 4 and 5 and Table 2. A variation on this management approach is the increased use of public information and education campaigns to encourage people, companies, and governments to voluntarily reduce energy use or reduce GHG emissions resulting from its use. This last will be referred to as MA1a and will be discussed further in Section 5.5.

(MA2) Government-determined De-carbonization

This management approach assumes that governments use their regulatory powers to decrease atmospheric GHG levels compared to what they otherwise would have been using executive actions or judicial decisions but do not assume responsibility for direct management of world climate. Since most of the actions would presumably be centered on reducing CO_2 levels, it is characterized as "de-carbonization" even though other GHG emissions would need to be considered as well. It is could further be described as "coercive" because the governments involved would have to find ways and means to actively encourage their citizens and economic units to decrease GHG emissions or to penalize those that did not.

(MA2a) Kyoto Protocol and Possible Follow-ons

This management approach assumes that the world attempts to implement the Kyoto Protocol and that similar follow-ons to it will eventually be negotiated. Since this is the most prominent of the de-carbonization alternatives, it will be discussed at some length in Section 3 and analyzed as remedy B in Sections 4 and 5 and Tables 1 and 2.

(MA2b) Decentralized Approaches

This management approach assumes that various local or sub-national governments take action to limit GHG emissions or force one or more unwilling national government to do so using existing laws. Or alternatively it assumes that one or a few nations decide to pursue an approach that is independent of those taken by any international body or uncoordinated with a group of nations with significant emissions. This will be assumed to be a sub-case of MA2a and will be discussed further in Section 5.5.

(MA2c) Liability-based Approaches

This management approach assumes that "tobacco-style" liability cases are successfully used to force major GHG emitters or manufacturers of GHG emitting equipment to reduce emissions in one or more countries. This will also be assumed to be a sub-case of MA2a and will be discussed further in Section 5.5.

(MA3) Engineered Climate Selection

This management approach assumes that one or more governments or an international governmental body with the economic and technological resources to carry it out select and implement desired climate/temperature regimes for the world using radiative forcing technology. It also assumes that there would be no effort at de-carbonization. It will be discussed as remedies F, G, and H in Sections 4 and 5 and Tables 1 and 2. One of the differences between this management approach and MA2 is that while international cooperation and coordination would be very desirable, one nation could indeed carry out a program to engineer effective climate selection for the whole world, although probably with great condemnation by other countries.

(MA4) International Approach Utilizing All Available Technological Approaches

This management approach differs from the others by allowing for the use of all of the other approaches and available technologies but creating a new rationale for doing so. The new rationale would be based on the application of the "polluter pays" principle and relative responsibility for climate change problems to determine the costs to each country.

1.3.2 Technological Approaches

At the risk of some minor oversimplification, there would appear to be only three general technological approaches towards controlling Earth's temperature climate:

> Alter world atmospheric GHG levels by:
>
> > (TA2a) Changing GHG emissions (referred to here as "conventional approaches" or "conventional de-carbonization" and discussed in Row B of Tables 1 and 2)
> >
> > (TA2b) Removing or sequestering GHGs already in or about to enter the atmosphere (referred to in this paper as "non-conventional de-carbonization" and discussed in Section 4.3.1 and in Row C of Table 1 and Rows C through E of Table 2),
>
> Or, (TA3) altering Earth's radiation balance through other means (referred to as "engineered climate selection" or "radiative forcing" and discussed in Section 4.3.2 and Rows F, G, and H of Table 1 and rows G and H of Table 2).

The first two (TA2a and TA2b) will be referred to as de-carbonization. The last two (TA2b and TA3) will be defined as "non-conventional" or geoengineering approaches. Radiative forcing is the change in the balance between radiation coming into the atmosphere and radiation going out. Note that (TA3) impacts only the temperature-related effects of higher atmospheric GHG levels as defined in Section 2.5, while (TA2a) and (2b) impact both temperature and non-temperature-related effects. It is also important to note that removing GHGs already in the atmosphere (1b) can be used to satisfy the requirements of the Kyoto Protocol but changing Earth's radiation balance (2) cannot. The Kyoto Protocol also does not give full credit for substitution of nuclear for fossil-fuel power sources, which are nevertheless included in group (TA2a) to simplify the analysis. There are a very large number of possibilities for reducing GHG emissions, which have been described in Hoffert et al. (2002) and other sources.

Engineered climate selection has often been referred to as geoengineering, which has been defined by David Keith (2000) as "intentional large-scale manipulation of the environment." There are a number of grey areas that fall between de-carbonization and geoengineering, but where in doubt they will be assumed to constitute geoengineering for the purposes of this paper. There are a large number of such proposals; this paper will briefly summarize only a few of the more interesting ones in terms of the criteria outlined in Section 1.1 involving either cooling or warming global temperatures since there are extensive summaries available elsewhere.

1.3.3 Remedies to Be Extensively Evaluated

In the interests of simplifying the analysis to manageable proportions, the two approaches towards control, management and technological, will be consolidated for the purposes of this paper into consideration of more limited general types of remedies that will be extensively analyzed. Since MA1 has a technological counterpart, which is not to apply technology, and MA3 also has a technological counterpart (TA3), the choice of remedies R1 and R3 are easy. R2 and R2a, however are more complicated. To simplify the analysis, this delineation omits the following management sub-options: MA1a, MA2b, MA2c, and MA4. Fortunately, these appear to be closely related in their characteristics to the options that are considered, so will be briefly analyzed in Section 5.5 after the analysis of the other options. This leaves the following remedies for the main analysis:

(R1) Non-stabilized "business-as-usual" carbonization and adaptation, based on MA1

(R2) Kyoto Protocol and possible follow-ons (MA2b) using conventional technology (TA1a)

(R2a) Non-conventional de-carbonization or sequestration (TA1b)

(R3) Engineered climate selection, combining MA3 and TA2

The primary comparison of these remedies is to be found in Table 2, which uses the criteria (used as columns in Table 2) outlined in Section 1.1 as the basis for the comparison of the remedies (used as rows in Table 2) discussed in Section 4. Figure 1 presents the economic benefit and cost aspects of results shown in Table 2 except that the tools/remedies are shown as vertical columns. Hoffert et al. (2002) provides a broad overview of the conventional and some of the non-conventional options available, with emphasis on energy production options. There are extensive review articles on both the rationale for using non-conventional approaches (Michaelson, 1998) as remedies for climate change and on the approaches themselves (Keith, 2000). An earlier discussion of some of these remedies can be found in NAS 1992. Posner 2004 provides a legal and economic perspective on some of the alternatives. Recent summaries of selected non-conventional options can be found in Tyndall 2004. Posner 2004 provides a legal and economic perspective on some of the alternatives. Recent summaries of selected non-conventional options can be found in Tyndall 2004. To the extent possible, the options are evaluated using peer-reviewed literature. Where this is not available, the proponents' statements are used as the basis for comparisons, but with the source noted.

This paper considers both how each of the four specific problems identified earlier in this section could be most effectively and efficiently addressed after reviewing a range of alternative solutions that have been proposed for the climate change control problem. The primary discussion of alternative climate change remedies is to be found in Sections 4 and 5. The general conclusions with regard to available alternatives can be found in Section 5.4, the application to other management tools can be found in Section 5.5, and the application to the four specific problems in

Section 5.6. The implications of the analysis for the choice of remedies are discussed in Section 5.7. Section 6 discusses some of the likely major objections to the use of engineered climate selection, and Section 7 presents a summary of the paper. The paper begins by briefly summarizes some of the relevant science (Section 2) and analyzing the prospects for the Kyoto approach (Section 3).

2. Climate Change: The Scientific Background

Although the purpose of this paper is not to survey the scientific literature on climate change, a brief discussion of some aspects provides useful background for the remainder of the paper. The emphasis in this Section is on the major causes and effects of global climate change both anthropogenic and natural.

2.1 "Recent" Earth Climate History

Much of the extensive discussion in recent years of global warming and what, if anything, needs to be done about it, seems to have been largely carried out as if the alternative to global warming is the climate that prevailed in the late 19th or early 20th Century or at most that which prevailed over the last 12 thousand years or so of the current interglacial or Holocene Epoch. This appears to ignore the larger reality that Earth has been gripped in a series of extended and worsening ice ages for the last 2.7 million years, so that the "norm" is not the gentle climate of the current Holocene years but the predominantly horrific climate of the last three million years since the present series of ice ages began (broken only by relatively short interglacial periods). Interglacial periods have accounted for less than ten percent of the past 900,000 years (Ruddiman, 2005a) and represent one extreme of this longer period—the warm extreme. And if the current Holocene interglacial period had followed the pattern of the last several, it would now be ending (Ruddiman, 2005a) with possibly disastrous consequences for further human development. In addition, there is evidence for a Holocene era 1,500-year periodicity in Northern Hemisphere temperatures, with the last minimum 400-500 years ago (Teller et al., 1999). During the previous interglacial period, there were several such "cold snaps" over intervals of a few decades without significant climatological precursors or warnings (Teller et al., 1999). So if "recent" history were the only guide, there is reason to be concerned that the current interglacial period may be near its end and Earth could be headed for another 100,000 years or so in the ice box, or that a new "cold snap" could occur during the current century (Teller et al., 1999). Since at least the first of these possibilities would seem to have much greater consequences than global warming, this paper examines the global warming question from a larger perspective of preserving as human-friendly a climate as possible rather than the more limited (but still important) objective of avoiding global warming that now appears to be occurring.

2.2 Explanations for Ice Ages

A number of hypotheses have been proposed to explain these periodic ice ages. The most widely accepted of these is the Milankovitch cycles, but others have suggested variations in the levels of cosmic dust entering Earth's atmosphere, and in solar output.[2]

A particularly comprehensive attempt to explain variations in global temperatures based on the Milankovitch cycles and human impacts can be found in Ruddiman (2005a). The important point is that basic causation has not been firmly established, or at least not universally accepted, and is the subject of continuing debate at the current time. It is therefore important that any remedies proposed take this uncertainty into account—hence the possible importance of a criterion allowing for flexible responses.

As so often happens in science, recent research includes some apparently contradictory findings concerning the current risk of returning to a new ice age. In 2003 William Ruddiman published a paper (Ruddiman, 2003) explaining his basic hypothesis, followed more recently by a book (Ruddiman, 2005a) setting forth a comprehensive explanation for observed GHG and global temperature changes that showed unusual changes in carbon dioxide (CO_2) and methane levels in Antarctic ice cores 5,000 to 8,000 years ago. He concludes that the CO_2 interglacial life cycle in the present interglacial has been different than the three other interglacials in the last 400,000 years in which CO_2 levels tended to peak in the early part of the interglacial and then either stabilized or gradually decrease. For the current Holocene interglacial, however, an early dip followed the first peak and then CO_2 levels started to go back up. Analysis of the methane record shows a similar unusual trend with respect to prior interglacials. He attributes the change to human activities of clearing forest cover and starting to irrigate for rice in Southeast Asia in that time period. Ruddiman (2005a) argues that the rise in global temperatures corresponding to the relative rises in CO_2 and methane levels starting 5,000 to 8,000 years ago was enough to keep the Earth from starting into a new ice age. He also associates subsequent brief drops in CO_2 and temperatures (such as the Little Ice Age) not easily explained by natural processes with the greatest pandemics in human history.

In 2004 Eric Wolff and colleagues announced the results of Antarctic ice core temperature measurements from an earlier period during the full MIS 11 interglacial period some 430,000 years ago.[3] They appear to believe that Earth's climate is primarily influenced by GHG levels in the atmosphere and the Milankovitch cycles, but have interpreted their work as showing that the current interglacial has similarities to the MIS 11 interglacial, and may last another 15,000 years, like it did. They further argue that those who argue that global warming is good because of its effects on warding off a new ice age are wrong because in their view there is no "immediate" threat of a new ice age given their 15,000-year estimate. Ruddiman (2005 and 2005a) agrees that the Milankovitch cycles were more similar to the current interglacial during the MIS 11 interglacial than during more recent ones, but disagrees with the Antarctic researchers' conclusions, saying that the MIS 11 interglacial started earlier than usual, but ended at a time entirely consistent with his hypotheses concerning the influence of the Milankovitch cycles on the initiation of ice ages. Some of Wolff's colleagues (Siegenthaler et al, 2005) have responded that an even earlier interglacial shows an increase in CO_2 levels similar to the Holocene increase cited by Ruddiman as anamolous.

2.3 How Long Will the Holocene Last?

The most recent scientific evidence discussed above concerning the reasons for Earth's "overdue" new ice age is at best confusing. If you accept Ruddiman's much more comprehensive explanation, then the logical conclusion is that the Holocene will last as long as humans keep burning fossil fuels and engaging in other GHG-generating activities at the current level, but may well end if and when fossil fuel burning greatly decreases. And in the meantime CO_2 levels will increase along with temperatures. On the other hand, if Wolff and colleagues should be correct, then the Earth may descend into a new ice age in about 15,000 years, just as it did 400,000 or so years ago. The important point here is that there is some uncertainty given current knowledge, which underlines the importance of a flexibility criterion for judging climate change remedies.

Both scenarios, however, suggest that warming rather than cooling is the most immediate threat, but that cooling could became a problem when and if fossil fuel use declines sharply, or in 15,000 years. Under either scenario, however, cooling remains a potential problem sometime in the future, but probably not in the immediate future.

2.4 Long Response Times for Climate System and Influence of Carbon Dioxide and the Earth's Radiation Balance on Climate

Response times are an important aspect of Earth's climate system and vary widely. The system responds very rapidly in terms of changes in ice cover on land, but very slowly in the case of the deep ocean. Because of the slow response times of many of the Earth's climate systems, there are long lags in the response of temperatures to changes in emissions and GHG concentrations (Ruddiman, 2005a). In the case of the long response components, any attempt to actively control climate change needs to take these long response components into account. It is likely that changes in CO_2 levels in the atmosphere, for example, are an important influence on global climate but with a fairly long lead-time. Although not the most potent GHG, it is the one that many scientists are most concerned about. Direct attempts to change the incoming radiation from the sun or the outgoing radiation reflected back into space from the Earth appears to be a more immediate means to influence global temperatures than changing carbon dioxide levels, however.

2.5 A Very Brief Overview of the Causes and Effects of Global Warming

The generally accepted theory of global warming is that global temperatures depend on the concentrations of GHGs in the atmosphere since these change the absorption of and retention of heat from the sun by the Earth. The GHG concentrations, in turn, are determined by the emission of these gases into the atmosphere minus their removal from the atmosphere. The effects of higher GHG concentrations be broken down into two major categories for the purposes of this analysis, which correspond to problems P1 and P2 delineated in Section 1.2:

(P1) Those that are a direct result of higher global temperatures.

(P2) Those that are the result of non-temperature effects of higher GHG concentrations in the atmosphere.

2.6 What Atmospheric GHG Concentrations Would Be Required to Avoid a New Ice Age?

An important piece of information in achieving any sort of "ideal" GHG management are what atmospheric GHG concentrations would be just sufficient to avoid another ice age since that would appear likely to have very adverse consequences for both humans and many current ecosystems. If Ruddiman is correct, the higher atmospheric levels already reached or likely to be reached with no change in GHG emission levels are more than sufficient for this purpose. Since CO_2 levels have not fallen below about 260 ppmv since his "natural" CO_2 peak about 11,000 years ago, and no new ice age has started, presumably 260 is sufficient to avoid any new ice age. Wood (2005) suggests that the critical level might be slightly lower, about 250 ppmv for CO_2.

2.7 Why Accidental Global Warming May No Longer Be Good

Ruddiman's research (summarized in 2005a) implies that Earth and its human cargo had a very narrow escape from the start of a new ice age, and entirely by luck and human activity undertaken for other reasons happened to escape what would have been an early end to modern civilization in the northern latitudes. Under this interpretation, human-induced global warming may have saved the day by avoiding a truly catastrophic new ice age rather than being the cause of the problem. But do we really want to run such risks in the future? Although it appears unlikely that a new ice age would start at current or foreseeable CO_2 levels, it is important to ask what if Ruddiman and Wolff are both wrong and a new ice age is only a few decades away given no intentional human intervention?

2.8 Instability, Lack of Full Understanding of Earth's Climate, and the Effects of Short-term and Unexpected Events

There appear to be substantial uncertainties in predictions of future climate changes. There can be little doubt based on the results of ice cores retrieved from Greenland and Antarctica that there have been substantial and sometimes abrupt (like a decade) climate variations in the past that cannot be explained by the Milankovitch cycles. The result is that it is now believed that ice ages can come on or end in as little as a few decades or even a few years (Alley, 2000).

There is also considerable debate about whether there may be adverse feedback (or triggering of "tipping points" where a slight rise in the Earth's temperature can cause a dramatic change in the environment that triggers a far greater increase in global temperatures) from global warming such that further warming would either accelerate global warming, or working in reverse, bring about an abrupt climate cooling (defined as problem P2 in Section 1.2). A number of concerns have been offered for this by Schellnhuber (ed.) (2006), Lovelock (2006) and others, including the following:

(1) Thawing of arctic permafrost may release methane, a potent GHG, which would promote further warming.[4]

(2) Arctic thawing may release sufficient fresh water so as to reduce or even eliminate the oceanic "conveyor belt" that brings warm water into the North Atlantic, warming Europe and North America and carries away cold, salty water into the South Atlantic and beyond. This could lead to a shift of the tropical rainfall belts.[5]

(3) Disintegration of the Greenland or West Antarctic ice sheets, resulting in a substantial rise in sea level, and, in the case of Greenland, possibly a reduction in the conveyor belt.[5]

(4) Loss of sea ice in the Arctic Sea, increasing absorption of sunlight and possibly changing major weather patterns.[6] Similarly, a decrease in land coverage of ice and snow would also increase the absorption of sunlight (Lovelock, 2006).

(5) As the oceans warm, the ocean area covered by nutrient-poor water may increase and algae growth decrease. This is likely to reduce the absorption of CO_2 by the algae and the generation of marine stratus clouds that reflect sunlight (Lovelock, 2006)

(6) Increasing global temperatures may destabilize tropical rain forests and lessen the area they cover and the global cooling they provide (Lovelock, 2006).

(7) The dark, heat absorbing, boreal forests of Siberia and Canada are likely to extend their range as global temperatures increase (Lovelock, 2006).

(8) Recent research suggests that most of the major mass extinction events in Earth's history may have been caused as a result of global warming when CO_2 levels reached about 1,000 ppm or above. At the current rate of increase, the Earth is expected to reach these

levels near the end of the next century (Ward, 2006). The extinctions are believed to be a result of the generation of hydrogen sulfide in the seas and its diffusion into the air.

The most recent of these mass extinctions occurred during a major period of global warming about 55 million years ago known as the Paleocene-Eocene Thermal Maximum, apparently also due to emissions of carbon gases. During this period average global temperatures increased about 5 to 8^{o}C (Lovelock, 2006) and the fossil record shows dramatic changes in plant and animal life, both on land and in the oceans.[7] In the oceans there was considerable acidification and loss of organisms with carbonate shells. The carbon emitted into the atmosphere during the period has been estimated as similar to the carbon emissions from fossil fuel burning over the next three centuries. The recovery time from these changes was about 100,000 to 200,000 years.

Whether any or all of these or adverse feedbacks exist or not is a subject of varying degrees of scientific conjecture, as is whether or when they may result in "tipping points." But if any of them appeared to be about to happen, humans would presumably be better off to take practical steps to try to avoid them rather than hoping for a miracle. In other words, there appears to be sufficient uncertainty concerning whether and when these events will happen that it is beneficial to be prepared to move decisively to avert pending problems if they should arise (assuming that nothing is done to prevent them in the first place).

In the case of (2), there has been increasing debate as to the causes of abrupt climate changes. Some (Broecker, 1997) have proposed that some of them could have been caused by a breakdown of the oceanic "conveyor belt" that brings warm water into the North Atlantic, warming Europe and Eastern North America, and carries away cold salty water into the South Atlantic and beyond. There are recent indications (Bryden et al, 2005) that the "conveyor belt" has weakened by about 30 percent in recent years, possibly because of an influx of less saline water into the North Atlantic as a result of global warming-induced thawing in the Arctic. The conveyor belt has broken down in the past. The best known example of this is the Younger Dryas cooling of about 12,000 years ago. This event began within a decade and for its 1000-year duration the North Atlantic region was about 5°C colder. Although this is not deemed to be an ice age in itself, it may have felt like one to the generations who lived through it and would certainly have large economic effects on Western Europe and possibly elsewhere if it should be repeated now. Unfortunately, it is believed that restarting the conveyor belt would take many years of much colder Arctic weather, as it did 12,000 years ago. This long lag to restart increases the damage that would be caused by a possible conveyor belt collapse. There is some doubt among scientists, however, that global warming could bring about a new collapse of the conveyor belt, but concern that global warming could result in other abrupt and serious regional climate changes.[8]

Despite considerable research to build better climate models, it appears safe to say that considerable uncertainties remain. One illustration of this is the debate over global dimming (Stanhill and Cohen, 2001), and the extent to which increased pollution in the Twentieth Century may have masked the impact of higher CO_2 levels on global temperatures. It is even conceivable (although probably unlikely) that if pollution should substantially decrease (as might be the case if a successful effort were actually made to decrease CO_2 emissions), the result could be an unexpected plateau in or even an increase in global temperatures as the dimming effect diminishes at the same time that GHG emissions decrease. Given the lag between changes in emissions and changes atmospheric concentrations of CO_2, in fact, this could happen in the early years of an effective effort to decrease global CO_2 emissions.

One known source of shorter-term climate cooling that is widely ignored in discussions of climate change is major volcanic eruptions that place sulfur-containing gases into the stratosphere (defined as problem P4 in Section 1.2). As a result of observations concerning the climatic effects of major volcanic eruptions such as El Chichon and Mount Pinatubo, which resulted in significant observed global cooling, it has been clear that sulfur-containing gases that reach the stratosphere from major eruptions cool the planet (Robock, 2002 and deSilva) although they are clearly dirty and involve grossly oversized aerosols lifted to a less than "optimal" altitude if the purpose were to decrease global temperatures. Sulfur combines with water vapor in the stratosphere to form dense clouds of tiny droplets of sulfuric acid. These decrease tropospheric temperatures because they absorb incoming solar radiation and scatter it back into space. The severity of the climatic effect depends on the magnitude of the eruption, the sulfur content of the magma, and the amount of sulfur released into the stratosphere as an aerosol. For extremely large eruptions, the climatic effects will persist until the sulfur compounds gradually drop out to lower altitudes where they are washed out by rain. In the case of major eruptions such as Mount Tambora in 1815, the climatic effects were observed in 1816, the "year without a summer." In the case of supervolcanic eruptions, the effects would presumably be much longer. The most recent one, the Toba eruption about 74,000 years ago, may have had extremely catastrophic effects according to extracts from Ambrose (1998):

> The last glacial period was preceded by 1000 years of the coldest temperatures of the Late Pleistocene, apparently caused by the eruption of the Mount Toba volcano. The six year long volcanic winter and 1000-year-long instant ice age that followed Mount Toba's eruption may have decimated modern man's population. Genetic evidence suggests that human population size fell to about 10,000 adults between about 50 and 100 thousand years ago. The survivors from this global catastrophe would have found refuge in isolated tropical pockets, mainly in Equatorial Africa. Populations living in Europe and Northern China would have been completely eliminated by the reduction in summer temperatures by as much as 12 degrees centigrade.

Although these effects occurred before humans kept accurate climate or population records, it would appear that even such short-term, natural events can have a greater impact on human welfare than are likely to occur from the current global warming. And unlike global warming, adaptation is very difficult in the case of major eruptions since their timing and size of effects are currently unpredictable. There can be little doubt that there will be future major volcanic eruptions that will affect climate. There were approximately ten in the 20th Century (Viner and Jones, 2000), or an average of one per decade. None of these ten were catastrophic in terms of their effects. De Silva states that it is generally accepted that there will be an average temperature decrease of 0.2 to 0.5°C for one to three years after a major eruption, although there is great variability between eruptions based on the factors mentioned in the preceding paragraph. This compares with an increase of global temperatures of about 0.6°C during the 20th Century. Although no estimate of the economic damages from such decreases is available, there are very likely to have been substantial costs, perhaps even as much as that for global warming to date given the greater difficulty of adapting to these effects. It is also highly probable, if not certain, that one or more future volcanic eruptions will at some time be a supervolcanic eruption.[9] Many scientists believe that such a supervolcanic eruption can be expected in Yellowstone National Park as well as elsewhere (Bindeman, 2006). Such eruptions have occurred about 600,000 to 700,000 years apart near Yellowstone, and it has been 640,000 years since the last one. When it occurs, it is expected to have catastrophic results for both the United States and the world. There is no known way to decrease the direct effects of such an eruption, such as pyroclastic flows and nationwide ash falls, but it would appear possible to prevent or reduce the indirect effects on global temperatures if immediate action could be taken to increase global temperatures when such eruptions occur. These indirect effects on global temperatures, sometimes described as a volcanic winter, would probably decimate agricultural production and thus human food supplies, something that the survivors would desperately need. It should be noted that the question appears to be not whether there will be future eruptions that will affect climate, but rather when and where they will next occur and how serious the effects will be. The risks of such adverse events are somewhat different from those of the other three problems listed in Section 1.2. There is a virtual certainty of short-term impacts of 0.2 to 0.5°C once a decade or so on average and a risk of extremely catastrophic events with a very much longer and even more uncertain time interval. There appears to have been few if any attempts to reduce these risks from volcanic eruptions. Somewhat similar effects on global temperatures may also occur as a result of either collisions with asteroids or nuclear war (where the effects are sometimes described as a nuclear winter).

2.9 What Might the Future Hold?

What can we conclude from this brief overview of climate change science? Global temperatures appear to be affected by both human activities as well as short and long-term natural events and forces. This makes predictions of future temperatures risky, although it is clear that they need to be viewed from both a much shorter and a much longer time horizon than that of the current warming period. Ruddiman (2005a) provides an extensive discussion of some of the possibilities. He agrees that warming is the principal threat in the next few centuries, but that an ice age is a longer-term possibility. It may be significant that the difference between the CO_2 levels prevalent in an ice age and an interglacial period appears to be roughly 80 ppm of CO_2, and that ice ages may be initiated by CO_2 changes of as little as 30 ppm below the levels prevalent in the interglacial periods. Humans appear to have increased CO_2 levels by another 100 ppm above those prevalent at the interglacial highs. Despite the lags built into the climate system, it is hard to believe that such a change will not have a major impact on climate at some point in the future. A new study (Bala et al, 2005) with a longer than usual time horizon concludes that a “business-as-usual” approach to the use of fossil fuels is likely to lead to a 14.5 degree F. rise in average global temperatures by the year 2300. It appears likely that the global warming that occurs will be interrupted every decade or so by unpredictable one to three year global cooling from major volcanic eruptions, and although much less likely, it is even possible that there will at some point in the future be a volcanic winter (as a result of a supervolcanic eruption) or other abrupt climatic change resulting in serious global cooling. There may also be “tipping points” where a continued rise in global temperatures will trigger very adverse environmental effects. It would therefore appear prudent for humans to consider how best to counter continuing global warming while at the same time developing the capability to counter shorter-term global cooling or warming on a rapid response basis.

3. Why the Kyoto Approach Will Not Prevent Climate Change and Is Unlikely to Achieve Its Goals

The most prominent current management tool to control global climate change is represented by the Kyoto Protocol, which seeks to limit emissions of GHGs by the wealthier nations. The next objective of this paper is to analyze the Protocol to see if it is likely to prevent climate change or to achieve the goals set for it. Most economists who have examined it have seen it as deeply flawed (Olmstead and Stavins, 2006). But before examining the Protocol, it is important to define what the “Kyoto approach” and “prevent global warming” mean as used in this paper.

3.1 What Is Meant by the “Kyoto Approach”

The “Kyoto approach” as used in this paper includes any control measure explicitly sanctioned by the Kyoto Protocol and approved implementing instruments.

3.2 What It Means to “Prevent Global Warming”

The common understanding of the phrase “prevent global warming” is presumably that global temperatures would not be allowed to rise beyond what they currently are. This is not, however, the definition used in the discussion of the United Nations Framework Convention on Climate Change (UNFCCC). Its much less demanding definition is that there be “stabilization of greenhouse gas concentrations at a level that would prevent dangerous anthropogenic interference with the climate system”. There are at least two other interesting definitions. One is that global temperatures return to what they were sometime in the less industrial past, say the second half of the 19th Century (3.23). An even more demanding one would be that global temperatures return to what they would have been without human activity of any kind (3.24). Each of these will discussed in the order of increasingly difficulty of achievement.

3.21 GHG Stabilization

The UN Framework definition of “dangerous anthropogenic interference” is a very slippery one since the effects on global temperatures depend on when the levels are stabilized and the GHG concentrations they are stabilized at, which in turn depends on what level is needed to “prevent dangerous anthropogenic interference with the climate system.” In other words, this definition does not prevent global warming in the common understanding of the phrase. Rather, it says that atmospheric GHG levels should be stabilized at a level that is not “dangerous.” The European Union has a target of restricting global warming to 2°C above pre-industrial levels, presumably because it believes that any temperature rise above that amount would be “dangerous.” Two bills introduced into the US Congress in 2006 similarly specify a similar goal of average temperature rises of no more than 2°C and stabilization of CO_2 levels at 450 ppm.[10] One obvious question is whether a reasonable solution to the global warming problem would be to change the interpretation of the goal so that warming above 2°C would be acceptable? The problem with this is that P3, the risk of abrupt climate changes resulting from higher average world temperatures, presumably increases as temperatures rise. So although there is no certainty that all abrupt changes can be avoided below 2°C, there is believed to be rapidly increasing risk above that level and no certainty that 2°C is entirely safe either.

3.22 Global Temperature Stabilization at Lower Levels

Although there is no current discussion of doing so, global temperature stabilization lower levels would require stabilization of CO_2 (and other GHG concentrations) at lower levels. If the stabilization were to be at current levels, CO_2 levels would need to be stabilized at no more than current levels (approximately 380 ppmv) or some other actions be taken that would yield comparable global temperatures. If it were to be at pre-industrial levels or where they would have been without human intervention, CO_2 levels would presumably have to be much lower, say 275-280 or 240-245, respectively, or other actions taken that would yield comparable global temperatures.

This last would probably soon plunge Earth into a new ice age, a fate almost certainly worse than global warming.

3.23 Global Temperature Stabilization at Pre-industrial Levels

Stabilization at pre-industrial levels would obviously require that concentrations of CO_2 and other GHG concentrations also be lowered to the levels existing at that time, say 275-280 ppm plus an added short-run decrease to compensate for the slow response times of Earth's various climate systems to current elevated levels, or some other actions that would yield comparable global temperatures. At the least this would require an end to all human GHG emissions associated with the industrial revolution, including air conditioning, mechanical transport, etc., or some other actions that fully compensate for all these human-induced sources.

3.24 Global Temperatures Returned to What They Would Have Been without Human Activity

Essentially this would require that CO_2 and other GHG concentrations be brought back to what they would have been without the presence of human activity plus the added shorter-term decreases needed to compensate for the slow response times of Earth's various climate systems, or some other actions that would yield comparable global temperatures. In the case of CO_2, Ruddiman (2005a) suggests that that number would be just above 240 ppm.

3.3 GHG Stabilization under the Kyoto Approach

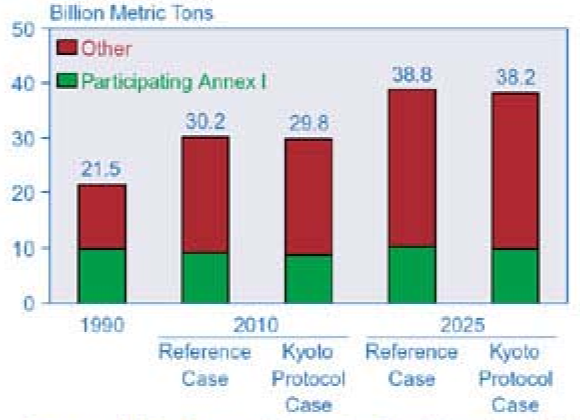
3.3.1 Kyoto Goals Unlikely to Be Met by Most Participating Annex I Countries

The first question to be asked is whether the emission goals specified in the Kyoto Protocol are likely to be met by the participating Annex I countries (i.e., those that ratified the Protocol and are obligated by it to make emission reductions)? Currently available information suggests that it is highly unlikely that the reductions specified in the agreement will be fully achieved in most of these countries. In November 2005 the European Environment Agency warned that the EU was likely to cut its emissions by only 2.5 percent by the year 2012.[11] In December the Institute for Public Policy Research concluded that ten of 15 EU signatories would miss their Kyoto targets without "urgent action."[12] An earlier 2003 European Environment Agency report reached the same conclusion.[13]

3.3.2 If Achieved for Participating Kyoto Annex I Nations, Goals Are Not Projected to Stop CO_2 Emission Increases

The most recent estimates of future world CO_2 releases assuming implementation of the Kyoto Protocol in participating Annex I countries and a continuation of it in future possible follow-on agreements suggest that CO_2 emissions will continue to increase (see attached Figure 6 from USDOE, 2005). Specifically, USDOE projects[14] that in this case world CO_2 emissions will increase 28 percent from 2010 to 2025 and 78 percent from 1990 to 2025 (as compared with a Kyoto proposed decrease of 5.3 percent). As long as emissions continue to increase, CO_2 concentrations will not fall. Other analyses of atmospheric con-

Figure 6. World Carbon Dioxide Emissions in Two Cases, 1990, 2010, and 2025



Sources: **1990:** Energy Information Administration (EIA), *International Energy Annual 2002*, DOE/EIA-0219(2002) (Washington, DC, March 2004), web site www.eia.doe.gov/iea/. **2010 and 2025:** EIA, System for the Analysis of Global Energy Markets (2005).

centrations of greenhouse gases also indicate that CO_2 would continue to increase (Caldeira et al. 2003, Bongaarts), although perhaps at a slower rate than they otherwise would.

The much more drastic reductions in overall fossil fuel use required for temperature stabilization (Caldeira et al. 2003, Bongaarts) are highly unlikely, particularly during a period when less developed country (LDC) use is rapidly increasing and is uncontrolled under the Protocol. Any "savings" from decreased developed country use are likely to be more than lost to Asian fossil fuel use increases (see Figure 65 from US-DOE 2006). The extra annual emissions of CO_2 from new coal-fired plants in China, India, and the United States are expected to exceed the projected reductions from Kyoto by more than a factor of five by 2012 (see "Extra Annual Emissions of CO_2" figure).[15]

Current projections of CO_2 releases by the International Energy Agency similarly suggest that the Kyoto targets will not be met on a worldwide basis.[16]

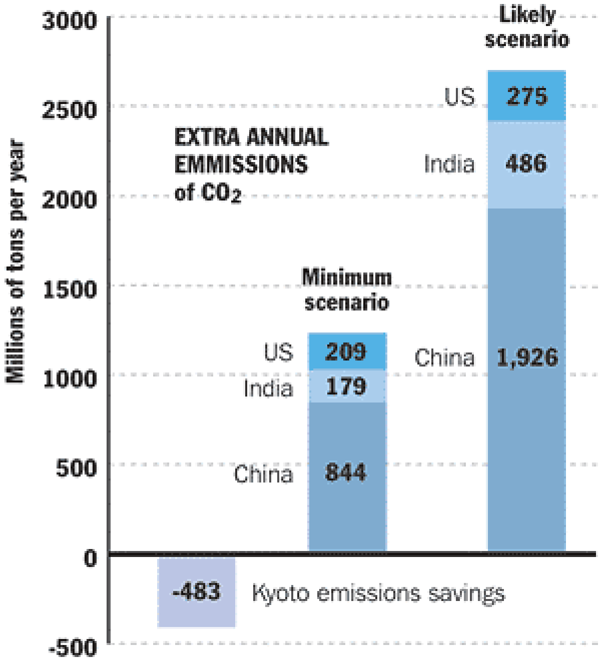
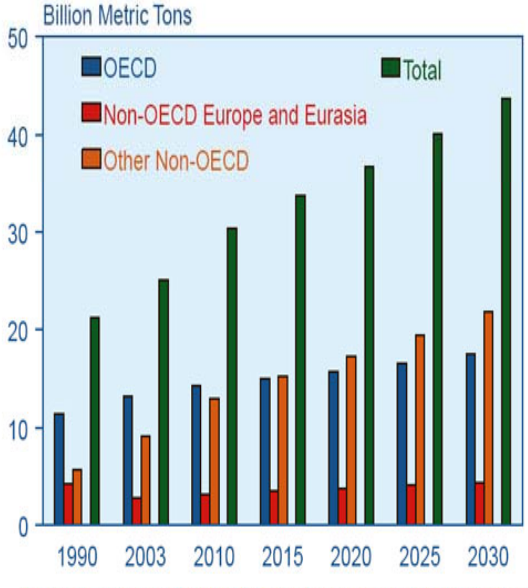


Figure 65. World Carbon Dioxide Emissions by Region, 1990-2030



Sources: **1990 and 2003:** Energy Information Administration (EIA), *International Energy Annual 2003* (May-July 2005), web site www.eia.doe.gov/iea/. **2010-2030:** EIA, System for the Analysis of Global Energy Markets (2006).

One study presented in early 2005 concluded that GHG emissions would have to fall to between 30 and 50 percent of 1990 levels by 2050 if there is to be a 50-50 chance of avoiding a temperature increase of more than 2°C.[17] That would mean a 50 to 70 percent decrease from 1990 levels and much more from 2006 levels. Greater assurance than a 50-50 chance of meeting the goal would require even larger reductions. The two bills introduced into the US Congress in 2006 specify a goal of an 80 percent reduction in CO_2 emissions by 2050 from 1990 levels in order to prevent more than a 2oC rise in temperature above the pre-industrial average and global atmospheric concentrations of GHGs (presumably they actually mean CO_2) from exceeding 450 ppm.[9] In other words, the average person in the world would have to decrease his/her direct and indirect GHG-emitting activities by two-thirds or even four-fifths at the same time that the developing countries are trying to rapidly increase their energy use. If, as the developing countries now insist, they continue to very rapidly increase their emissions, the percentage reductions required by the developed world would be still greater. Caldeira et al (2003) conclude that even if climate sensitivity is at the lower end of the range of uncertainty, over 75 percent of primary power would need to come from non-CO_2 emitting sources if the $2^{o}C$ goal is be met. And if climate sensitivity is at the higher end of the range of uncertainty, "nearly all of our primary power will have to come from non-CO_2 emitting sources." Put in simpler terms this would mean that nearly every electric power plant would need to be replaced with a hydro, wind, or nuclear-based facility. This strongly suggests that trying to meet the $2^{o}C$ goal using this approach would be somewhere between extremely difficult and impossible. Shinnar and Citro (2006) estimate that $170-200 billion per year would be required to achieve a 70 percent reduction in US CO_2 emissions over 30 years. Presumably if other countries did not meet similar reductions, the US would have to achieve much higher percentage reductions if the $2^{o}C$ goal were to be met. So I am not saying that it is impossible—just extremely expensive and impractical unless the population is placed on a freedom-of-choice limiting energy rationing system such as has recently been discussed in Great Britain[17] and the rest of the world (including the developing nations) achieves similar reductions.

The response of those advocating GHG emission control has been to argue that improved technology will come to the rescue.[19] More generally, proponents of Kyoto explain that Kyoto was never intended as the ultimate solution to global warming, but rather as a first step down a path that would ultimately lead to achievement of the UNFCCC goal. They hope that possible follow-ons to Kyoto will involve much greater GHG emission reductions that would make this possible. Whether there will be follow-ons is uncertain at this time, although the COP11 meeting in Montreal in late 2005 was not particularly encouraging in this respect. A further question is if there should be follow-ons whether they would be more strict or effective appears very doubtful.

3.3.3 Even if the EU/UNFCCC Goals Were Somehow Achieved Worldwide, There Would Still Be a Substantial Risk of Temperature Exceedences

Hare and Meinshausen (2004) conclude that only by stabilizing equivalent CO_2 levels below 450 ppm can the risk of overshooting the $2^{o}C$ target be termed "unlikely." Even at 450 there is a roughly 28 to 78% risk of overshooting the target, they calculate. Thus atmospheric concentrations nearer 400 ppm would be much more likely to result in meeting the target.

Worldwide CO_2 emissions are projected to increase at roughly 2 percent per year in the period 2002-2025 (USDOE, 2005) and CO_2 levels were at about 380 ppmv in 2004. Continuation of current emission levels are projected to result in the $2^{o}C$ target being exceeded in the late 21st Century (Hare and Meinshausen, 2004) after taking into account the slow response times. But since emission levels are increasing, not constant, the target would be exceeded earlier in this century according to these projections.

If the Kyoto goals were achieved on a worldwide basis (not just in participating Annex I countries) by 2012 and emissions were maintained at that level thereafter, it is possible that atmospheric concentrations might be stabilized at the 550 level, which would be very likely to result in an overshoot of the target (Hare and Meinshausen, 2004).

But the Kyoto goals currently only apply to industrialized participating signatories to the Protocol, whereas much of the increase in CO_2 emissions are projected to come from the less developed countries in coming years. "Mature market economies" are projected to increase their CO_2 emissions by 1.1 percent per year over the period 2002 to 2025; "emerging economies" are projected at 3.2 percent including China at 4.0 percent (from the base case of USDOE, 2005)

3.3.4 Successful Achievement of Goals Too Demanding of People and Their Governments

Attempting to control CO_2 and other GHG concentrations using the Kyoto approach to levels that would meet the EU/UNFCCC goals would require a large measure of international collaboration, willingness of governments to ignore their countries' self-interest, and willingness of billions of people to make personal sacrifices which do not now exist and may never exist. The benefits made possible by CO_2 emissions are basic to modern civilization, which provides huge economic incentives for continued increases. Efforts to control CO_2 emissions suffer from the immense costs of shifting modern society away from its increasing dependence on fossil fuels as a source of energy for economic growth and development. Significant progress assumes that people would agree to and actually implement greatly decreased fossil fuel consumption, which assumes that people would be willing to give up some of the very real benefits they enjoy from the use of fossil fuels at current or higher levels without a clear-cut, immediate "crisis" to spur them into making such sacrifices. The following quotation from Ruddiman, 2005a, explains some of the problems very well from the point of view of someone with as intimate a knowledge of the GHG emissions reductions that would be required as probably anyone:

> [There is] "an unspoken truth about global warming that for some reason politicians of both parties ignore. To reduce current and further greenhouse-gas emissions to levels that would avoid most of the projected future warming, draconian economic sacrifices would have to be enacted that almost everyone would find intolerable: much more expensive fuel for travel and heating, much lower/higher thermostat setting in houses and workplaces, and extremely costly upgrades (or total replacements) of power plants. The drag on the economy and the quality of life from such efforts would be enormous, and few citizens would stand for it. At this time, with current technologies, we simply cannot afford the effort that would be required to mitigate the main impact of global warming."

This paragraph points up one of the fundamental problems in the current approach to climate change problems by most of the developed world. Almost no one except Ruddiman has tried to explain the magnitude of the problem if GHG emissions are to be reduced sufficiently to avoid both warming and adverse climate feedbacks/"tipping points." An effective GHG emission control approach is not a matter of maintaining the current lifestyle in the developed world with a few adjustments and the use of more energy saving technology. As discussed in Section 3.3.2, it would rather require wholesale changes in lifestyles in the developed and radical changes in the development efforts by the less developed world as well as the introduction of most available technology, probably regardless of how expensive it may prove to be. It is hard to overemphasize the importance of this reality. As Ruddiman says, this is "an unspoken truth."

A more analytical approach might separate the GHG reduction problem into two components:

(1) Those measures involving achieving roughly the same level of individual welfare and personal freedom to choose at a lower cost in GHG emissions. The disadvantage of such reductions is that they will usually increase the costs involved, which usually have an indirect effect on living standards, as well as on international competitiveness if not undertaken by everyone in the world. Examples include substituting nuclear power for fossil fuel based electric power.

(2) Those whose primary effect is to lower individual welfare and freedom of choice by directly discouraging people from using energy for purposes that they have previously used it for and would like to continue doing so. These are likely to result in considerable pub-

lic dissatisfaction. Examples include discouraging people from making out-of-town trips (or using particular modes to do so), reducing use of automobiles in favor of other forms of transportation, or instituting an “annual carbon allowance” as Great Britain is said to be considering.[18]

The reason for making this distinction is the difference in the political impact of these measures. In sufficiently wealthy countries where the change in energy costs may not have a large impact on the public, it may be possible for politicians to persuade their constituents to accept some measures involving (1) but it may be almost impossible to do so for those involving primarily (2). But in many less developed countries where prices of electricity, heating oil, and other forms of energy are already being subsidized, even increases prices due to (1) are likely to be politically unpalatable. Even in wealthier countries, politicians are likely to be very cognizant of increases in energy prices that are likely to make the country less competitive internationally. They will probably favor price increases which will not have a major impact on the price of exports and where there is no international source which could provide a substitute good or service at a lower cost. Electricity generation is probably a good example. Such increases have only an indirect effect on competitiveness.

There are strong economic incentives not to reduce GHG emissions. The increasing use of fossil fuel energy to replace animal and human power has been one of the hallmarks of modern civilization. It has occurred because there are strong economic incentives to do so. These incentives could be changed by government actions, but they are so fundamental that this might prove to be very difficult to bring about. As illustrated by the current problems by many EU countries in meeting their commitments, politicians would be required to maintain unusually strong resolve and actually implement the reductions, even if agreed upon, as the population learns what the real effects of the measures would be on them. Under current circumstances, politicians can argue that higher energy prices are a result of the operation of the laws of supply and demand in the marketplace. But if markedly higher prices or energy use restrictions were imposed by politicians for the purpose of reducing global warming, they would be faced with a much more difficult situation. It is difficult to see why politicians would be willing to force their constituents to adopt unpopular and expensive constraints on their activities, or why many of their constituents would not pursue every available loophole or other avenues to avoid observing the constraints that are imposed. In the cases of type (2) measures, grandmothers may not agree that trips to see their grandchildren on the opposite coast can be dispensed with, particularly if politicians (and their possible future environmentalist supporters) do not fully explain in advance the degree of sacrifice that would be required. If the estimates of “needed” reductions in GHG emissions discussed in Section 3.3.2 are correct, it appears unlikely that all the reductions could be implemented in type (1) ways, but would require use of some type (2) measures as well. In other words, effective action under the Kyoto approach appears to assume that individual citizens would cooperate in ways that would involve significant sacrifices of personal freedom to choose. In this regard it may be important to note that global warming is currently perceived by the American people as a very low priority problem, even among environmental issues despite widespread knowledge that the effects of global warming have already begun.[19] Global warming has all the psychological characteristics (a long time horizon in human terms, uncertainty, familiarity with temperature changes, and no clear and very visible effects that constantly remind people that there is a problem that needs to be solved) that are likely to keep it at a low priority level.[16] Weber (2006) also believes that there are underlying psychological reasons why global warming does not scare people. The economic costs of the large GHG emissions reductions required to meet current interpretations of UNFCCC goals would be enormous—so much so that very few countries would willingly undertake them, particularly if all countries did not.[20] Achievement is unlikely to occur given the difficulty of instituting and using weak international bureaucratic systems to cope with strong economic incentives to use fossil fuel energy and other processes that release greenhouse gases.

Because of very slow response times by many components of the Earth's climate, the effects of GHG emission reductions will be a long time coming and will only gradually affect those changes that have already occurred. Proponents argue that the Kyoto Protocol is a useful first step down a long road, but given the larger picture it seems reasonable to ask whether it is useful if the stabilization of GHG levels in the atmosphere and therefore the mitigation of global warming are not likely to meet current interpretations of UNFCCC goals.

In many ways, the Kyoto approach to global warming assumes that CO_2 and other GHGs are just another set of pollutants that need to be controlled. The approach taken in the Kyoto Protocol is the rollback approach used often in many previous pollution control efforts. Where reasonably-priced alternatives exist or the cost of non-use are not prohibitive, this approach has indeed worked well in many developed countries for other pollution problems. But because of the central role that fossil fuel use plays in modern civilization and that greenhouse gases play in Earth's climate, GHGs are not just another set of pollutants. GHG emissions control therefore requires a careful reexamination of what it is that is to be achieved and the best means for doing so. The pollutant control approach is not only unlikely to succeed but is also extremely expensive as well as probably not meeting economists' larger objective of maximizing human welfare (see Section 5.1 below for a discussion of the economics involved).

3.3.5 Lack of Effective International Enforcement/Payment Mechanism

It appears unlikely that even if there should be a follow-on to Kyoto that it would be any more successful. The reason for this is that it is difficult if not impossible to conceive of a mechanism for ensuring compliance with any global scheme adopted (Lane, 2006). And without an assurance of effective penalties or other incentives, there will be overwhelming incentives for nations to "free ride" on contributions by others (Barrett and Stavins, 2003). Kyoto does not effectively address this problem either for participating Annex I countries or others. Presumably the reason is that there was no way to do so. The idea that "moral shame" will somehow persuade large CO_2 emitters like the United States, India, or China to undertake costly and politically painful mitigation efforts appears highly dubious. But without strong international penalties/incentives any Kyoto follow-on is equally likely to founder at the cost of the additional time that it will take for this to become apparent to everyone involved. Presumably one way to provide incentives to the less developed countries would be to offer large incentive payments from the major economic powers. But who would be willing to provide them given the "free rider" problem? The United States is not known for high levels of foreign aid, the budget category that these expenditures are likely to be lumped into, and which already is being used to further many other objectives. It appears equally unlikely that the participating Annex I countries would be willing to foot the bill by themselves.

3.3.6 Lack of Support From Major GHG Emitters

The lack of support by the United States and the lack of emissions reductions required by rapidly growing countries of Asia pretty much dooms the Kyoto Protocol in its present form from playing any meaningful role in controlling climate change. Without active GHG emissions reductions by at least India, China, and the United States it is extremely doubtful that anything meaningful can be achieved. One reason that the United States is not participating is the lack of a contribution from the other two. This argues that the cause of global climate control would be better served by substituting a different approach based on incentives rather than governmental coercion, a sharing of the burden based on past and present contributions to the problems, and the ability to use a wider array of technological approaches to solve the problems. The advantage of incentives is that those faced with the lowest cost of control would do the controlling rather than those who happen to have been allocated the most stringent quotas. Coercion is likely to result in more resistance than progress. And contributions based on the share of the problem caused would make the rationale explicit and possibly even "equitable."

3.3.7 Weak Basic Rationale

One of the basic problems with the Kyoto Protocol is the lack of a careful rationale for the approach used. This appears to be one of the reasons that the United States has rejected participating in it. Viewed as a purely technical issue, the damages from CO_2 emissions are caused by the additional emissions to the atmosphere. A good case can be made that any emissions of it, past or present, have roughly the same adverse effects since the time that CO_2 concentrations exceeded "normal" levels. Although CO_2 is lost each year, primarily to the oceans, it now appears that this has adverse effects too (Royal Society, 2005). A rough cut at an "equitable" system to allocate damages might be to sum anthropogenic CO_2 emissions since the diversion from "normal" levels for each country. This would result in the largest allocations to those countries with the greatest and longest standing emissions. But it would not exempt the developing countries either. But instead Kyoto completely exempts developing countries and sets what appear to be arbitrary limits on emissions from developed countries. The "equitable" system just discussed would place a significant penalty on developing countries with large emissions and encourage them to cut their emissions while placing the major burden on countries with substantial and longstanding emissions (like the US). Although estimates of these previous emissions are inherently uncertain, it appears possible to make useable estimates and therefore country allocations. This approach would at least create a credible rationale for the allocation of the costs of climate control between countries.

3.3.8 Partial Exclusion of Nuclear Power and Exclusion of International Aviation and Shipping Fuels

The Kyoto Protocol excludes nuclear energy under two of the three "flexibility mechanisms" that can be used by participating Annex I nations to meet their commitments. Nuclear power is one of the few possible substitutes for fossil-fuel power to supply base load power, so giving it second-class status further constrains the possible solutions to the climate change problem. The Protocol also excludes any consideration of emissions from international aviation and shipping fuels. International aviation and shipping are both growing sources of GHG emissions, and their exclusion places an increased burden on the remaining sources.

3.4 Global Temperatures under More Restrictive Regimes

As outlined above, global temperature stabilization at less than a $2^{o}C$ increase over pre-industrial levels appears extremely unlikely under the Kyoto approach. Accordingly, stabilization at lower levels required to meet the more restrictive definitions of stabilization is even less likely given the current Kyoto approach. Global temperature stabilization at pre-industrial levels could theoretically be achieved over time by reducing anthropogenic emissions to zero; even then it would not be achieved by 2400 because of the unrealized warming inherent in past emissions (Hare and Meinshausen, 2004).

Returning global temperatures to what they would have been without human activity would require either that emissions be reduced even below pre-industrial levels to the levels that would have existed without any human land clearing and plant cultivation activities. This is next to impossible using approaches sanctioned by the Kyoto Protocol given the needs of the billions of humans now on the planet and would probably result in time in a new ice age, which would definitely have strong adverse effects on humans and their physical assets.

4. Some Alternative Approaches for Controlling Climate Change

If the Kyoto approach will not prevent climate change or even mitigate it to the extent envisioned, and prevention/mitigation is something that humans want to achieve, what are some of the other tools available to control climate change and how should they be evaluated? In order to examine this question it is important to first examine the criteria to be used in determining this. Section 1.1 outlined the proposed evaluation criteria; the remainder of Section 4 discusses the primary remedies/tools/approaches that have received some attention and which are to be evaluated in this paper.

4.1 Non-stabilized “Business-as-usual” Carbonization and Adaptation (R1)

This ”remedy” assumes that no significant changes will be made in the current situation in which GHGs continue to be released into the atmosphere as rapidly as in the recent past and few are removed except through natural processes. This means increases in atmospheric CO_2 levels of 2-3 ppm per year.

4.2 Kyoto Using Conventional De-carbonization Technology (R2)

This remedy assumes that the management approach is that provided by the Kyoto Protocol but that only “conventional” technological approaches (TA1) are used to control climate change plus nuclear power (which Kyoto does not encourage).

4.3 Non-conventional De-carbonization or Sequestration (R2a)

4.3.1 CO_2 Sequestration

Several alternatives have been proposed (see Keith, 2000 and IPCC, 2005 for an overview) to increase the absorption of carbon dioxide from the atmosphere by plants. CO_2 and presumably other GHGs can also be removed from the atmosphere and directly stored in a number of places. CO_2 can also be removed from fossil fuel burning emissions before reaching the atmosphere. This last may not constitute geoengineering as the term is used elsewhere since it can be viewed as source mitigation, but this distinction will be ignored in this discussion.

4.3.1.1 Using Artificial Sequestration (Remedy C)

A number of ideas have been suggested for artificial sequestration of CO_2, including terrestrial, non-biological sinks located in a number of geological formations including depleted oil and gas fields, deep coal beds, and deep saline aquifers. In addition, there is the possibility of oceanic non-biological sinks using very deep areas of the oceans. Finally, there is the possibility of neutralizing the acidity of the carbonic acid resulting from dissolving CO_2 in water and disposing of the neutralized compounds into the ocean (Rau et al, 2001).

4.3.1.2 By Enhancing Natural Sequestration

Although a wide variety of proposals have been made, the principal proposals for terrestrial biological sinks involve intensive management of forests or other terrestrial ecosystems to stimulate their removal of CO_2 from the atmosphere beyond what would otherwise take place naturally (remedy D). The principal proposals for natural oceanic sequestration involve fertilizing the ocean surface with phosphate or iron in order to stimulate algae growth by supplying a biologically limiting nutrient (remedy E). The algae ultimately fall to the ocean floor as organic matter carrying carbon absorbed from the atmosphere with them. More algae mean more carbon sequestered.

4.4 Engineered Climate Selection or Changing Earth's Radiation Balance Directly (R3)

To the extent that there is a need for preventing/mitigating only the temperature-related effects of global warming, there is strong evidence that this can be done by altering Earth's radiation balance. This has been discussed as long ago as 1979 by Dyson and Marland and perhaps most prominently by the National Academy of Sciences global change study group (NAS, 1992), which noted what appeared to them to be its surprisingly great practicality. There are a variety of proposals to change the World's temperatures by altering either the heat coming into the Earth from the sun or changing the amount of heat reradiated back into space from the Earth. It is important to note that this approach differs from the previous ones in that GHG levels in the atmosphere are not directly altered. Only three of these proposals will be discussed here in order to simplify the discussion, but it is highly likely that there are others that have or will be proposed of equal or greater merit. So these proposals should be viewed as illustrative of the possibilities available and not as a definitive list of the only ones possible.

Teller et al. 1997, 1999, and 2002, Wood's presentation in Tyndall 2004, and Wood 2005 and 2005a (collectively referred to hereafter as the Livermore papers), suggested and explored the feasibility of engineered climate selection approaches to altering Earth's radiation balance to affect climate. To counteract global warming, Teller et al. advocate allowing a little more of Earth's thermal radiation to pass out of the Earth and/or allowing a little less of the Sun's in. To counter global cooling, they suggest allowing a little less of Earth's thermal radiation out and/or a little more of the Sun's in. This discussion concerns only a few of these proposals, which will be referred to as "radiative forcing" in this paper, and is intended to include the most attractive proposals found in the Livermore papers involving the stratosphere.[21]

4.4.1 Dispersing Sulfur Dioxide into the Stratosphere (Remedy F)

As discussed previously in Section 2.8, it has been clear that sulfur-containing gases that reach the upper atmosphere from major volcanic eruptions cool the planet (Robock, 2002). Human dispersion of such gases, presumably in a more optimized formulation, should have the same effect. Such approaches have been discussed in the Livermore papers, NAS (1992), and most recently by Crutzen (2006).

4.4.2 Optimized Radiative Forcing Using the Stratosphere (Remedy G)

The idea in remedy G is to add "optimized" particles to the stratosphere that would affect various parts of the thermal radiation passing through it. The authors suggest using particular types of very fine particles that would reduce the amount of ultraviolet light striking the Earth's surface, and offer a number of suggestions as to how they would be inserted into the stratosphere. The Livermore papers further argue that variations in the latitude where the substances are dispersed would make it possible to change global temperature distributions if desired, although this proposal is not part of the remedy considered here and could raise significant issues of who would lose and who would gain.

4.4.3 Optimized Radiative Forcing Using Space-based Deflector (Remedy H)

Some of the earlier Livermore papers also describe another option[22] involving the positioning of a specialized deflector between the Earth and the Sun to change the amount of sunlight reaching the Earth. The authors believe that this could be built in a very flexible manner to allow for either increasing or decreasing the sunlight reaching Earth as required.

5. A Comparison of Some of the Alternatives for Controlling Climate Change

It is surprising how little attention has been given to engineered climate selection approaches to global temperature control involving changing Earth's radiation balance given the widely reported problems with the more "conventional" approaches. With a few exceptions, these geoengineering approaches have generally been ignored, dismissed out of hand, or at best recommended for more research.[23] Although more research would be desirable, enough is known to suggest many of the advantages and disadvantages of these approaches. Some of the less attractive proposals are accorded only brief attention here. It should be noted, however, that the costs and benefits of various specific opportunities to reduce global warming vary considerably even within a single option, so that there may be "attractive" opportunities within remedies that do not appear to be generally attractive.

5.1 Non-stabilized "Business-as-usual" Carbonization and Adaptation (R1) and Kyoto Using Conventional De-carbonization Technology (R2)

Remedy R1 is assumed to be the base case in this analysis, so that the benefits and costs of this "remedy" are assumed to be zero. Given the likely ineffectiveness of R2, R1 currently appears to be the most probable approach that the world will follow, primarily as a result of inertia and the lack of an imminent disaster. As outlined in Section 2.9, this appears likely to result in increasing atmospheric CO_2 levels, increasing ocean acidity, and rising global temperatures.

A number of the characteristics of R2 (shown as remedy B in Table 2 and Figure 1) have already been discussed extensively in Section 3 above since the emphasis under the Kyoto approach is what I have defined as "conventional" approaches. The results of some of the others, such as those discussed in Section 5.2 below, could theoretically be counted under the Protocol, but are not usually actively considered for major roles in implementing it. One of the most apparent aspects of the "conventional" approach is that the outcome is uncertain since it depends not only on what actions various governments and individuals actually take but also on how the resulting changes in emissions impact global temperatures. Current discussions of implementing Kyoto usually center around the use of a "cap and trade" approach that has a good chance of minimizing the costs involved because of the inherent efficiency of using economic incentives. But since the methods to be used are necessarily unknown, the results are also uncertain and hard to predict--clearly a disadvantage of these "conventional" approaches relative to those involving changing Earth's radiation balance since they should yield much more direct control over global temperatures. In summary, remedy B does poorly against most of the criteria, since it has negative efficiency, low cost-effectiveness, poor environmental outcome, little equity, little flexibility to meet new conditions or possible global cooling, and places a great burden on participation and compliance. As noted in Section 3, the current indications concerning implementability are not too encouraging.

The costs of implementing this approach are very much dependent on how rapidly the GHG emission mitigation efforts are assumed to be implemented and on the percentage reductions assumed to be needed. Kolstad and Toman (2001) argue that marginal control costs increase with the percentage of carbon emissions controlled and may exceed $400 per ton for percentages in the range of 18 to 31 percent depending on the regions of the world involved. Since considerably more control would be required to stabilize temperatures, their study would suggest that marginal costs would exceed $400. Fischer and Morgenstern (2005) analyze 11 different studies and also find that control costs increase with the percentage reduction in carbon emissions. For abatement above 25 percent, the range of marginal costs is from just under $50 to $350 per ton in the United States. The reason that marginal costs vary with how rapidly mitigation is undertaken is that controlling GHG emissions can be most economically undertaken when the equipment that is producing the emissions needs to be replaced for other reasons. If the replacement is undertaken on a hurried or urgent basis without regard to these other reasons for replacement, the cost is much higher than those indicated earlier in this subsection. If the replacement occurs for other reasons, the marginal cost is only the added cost of the GHG reduction features of the new equipment. If, however, the current equipment would otherwise not need to be replaced, then the entire cost of the replacement should be counted against the cost of controlling GHGs. When one is dealing with tens of thousands of very expensive thermal electric power plants or hundreds of millions of motor vehicles or hundreds of millions of home heating and air conditioning units urgent replacement quickly becomes astronomically expensive. It is assumed in this paper that marginal costs are likely to be $50 to $400 per ton carbon. Lasky (2003) reviews a large number of cost studies that show estimated costs in this general range. Although it is not always clear whether estimates are based on long-term replacement costs (just the added cost of replacing high emission components with low emission ones), most available estimates appear to be so based. One of the most comprehensive recent studies of actual opportunities for reducing emissions (Socolow, 2005) quotes costs of $100 per ton carbon. Deutch and Moniz (2006) estimate that a carbon tax of about $100 per ton carbon would equalize the cost of electricity from nuclear, coal, and gas sources.[24] This is significant given that nuclear is one of the few technologies currently available that can substitute for fossil fuel-based base load power plants. Although it carries its own environmental risks, there may well be a trade-off that would have to be made between the risks of CO_2 emissions and nuclear power. Shinnar and Citro (2006) estimate that a carbon tax equivalent to $165 to $180 per ton carbon would be required to achieve a 70 percent reduction in CO_2 emissions over 30 years. Some earlier studies (Manne and Richels, 1992) found that stabilizing global CO_2 emissions would require a carbon tax in the range of $200. The important point here is not the upper bound (which depends on both the speed of mitigaton and the percentage reduction, and could rapidly reach astronomical levels under extreme cases) but rather that the marginal cost is not likely to be less than $50 per ton of carbon removed. Based on a broad review of the literature, Tol (2003) concludes that marginal benefits of carbon dioxide control of $15 per ton “seem justified,” and $50 or more per ton “cannot be defended with our current knowledge.” But even so it appears safe to conclude that the net benefits would be at least negative and probably strongly negative for option B. Although the approach, methodology, and values given by Nordhaus (1999) are different, his conclusions appear broadly consistent with Tol’s findings since he finds that the benefit-cost ratio for the Protocol is 1/7. At the same time, it must be emphasized that both the Tol benefit estimates and the cost estimates used in this paragraph are far from precise or generally accepted. Although they may well be the best currently available, the uncertainties are substantial. Readers are therefore encouraged to also use this analysis as a way of thinking about the problem rather than the last word on each of the values used.

One difference between remedy B and the others is that B might result in reduced use of petroleum (depending on which actual reductions in fossil fuel use were actually implemented). Since the later remedies on the list do not involve reducing energy use, it may be reasonable to include such benefits under remedy B to the extent that petroleum use would actually be reduced. Presumably these benefits would primarily involve increased security resulting from decreased reliance on insecure or unstable sources of petroleum. It is next to impossible to estimate these benefits because it is difficult to estimate the extent to which reductions in petroleum use would be used to meet Kyoto goals, the extent of the increased energy security, or its value. But these benefits should be considered as non-quantified benefits of remedy B.

It should be noted that there are almost certainly some low cost "conventional" opportunities in a wide range of areas, and some of them might even be comparable to some of the low-cost geoengineering options discussed below. There may even be some "conventional" opportunities where the private benefits exceed the private costs, although economists argue that they would have been already implemented in a perfectly competitive world if they were known to exist. The cost estimates shown in Table 1, Row B should be regarded as an attempt to bound the marginal costs needed to achieve the goals of the UNFCCC as interpreted by the EU. In other words, what is the cost of the most expensive "conventional" remedy that would have to be used to result in goal achievement (presumably that needed to limit temperature rise to 2^{o}C) where the lower cost remedies are used first? Because the CO_2 reductions under this option/remedy are varied and unpredictable given the learning curve that would undoubtedly evolve should implementation be attempted, there is no engineering estimate that can be made as to what the marginal cost would be. Rather, such estimates are at best guesstimates based often on model simulations. By contrast, most of the other remedies/options considered in this paper can be more reliably estimated using engineering cost estimates since somewhat similar technologies are likely to be used on each project that might be implemented. Accordingly, the full range of estimated costs is shown for each of the other remedies rather than the marginal cost.[25]

To the extent that there exist low-cost opportunities to lower GHG emissions using conventional means, these are certainly worth pursuing. This will not be mentioned further but almost goes without saying. But it appears highly unlikely given the currently available research on marginal costs that enough low-cost opportunities exist to meet the GHG reduction goals. Substituting more efficient light bulbs and reducing power used to keep appliances instantly available, if indeed these are very low-cost, can only reduce GHG emissions a limited amount. But it is economically rational to pursue any energy efficiency project that can be justified in terms of the benefits of reducing the non-temperature effects of GHGs. Since the temperature effects can be controlled at very low cost using other options, these effects are unlikely to justify more than the lowest cost conventional measures.

Remedy B is particularly ill-suited to situations where there is likely to be any significant change in the urgency of remedial actions because of the huge costs involved and the lengthy delays that would be needed to adjust the time frames, the country quotas, the particular regulations and incentives, and the actual investments by each individual country, industry, and individual. So to the extent that reducing climate change may be urgent (such as might be the case if there should be an abrupt climate change due to a volcanic eruption or other causes), the conventional approach to reducing it becomes even less attractive than it otherwise would be and perhaps even useless in the extreme case.

5.2 Non-conventional De-carbonization or Sequestration (R2a)

In general, CO_2 sequestration offers slightly more flexibility than the conventional approaches since implementation requires only initial agreement among those nations involved, and individual citizens do not have to make decisions contrary to their immediate self-interest. But it is nevertheless difficult to see how it could be effectively used to respond to abrupt changes in conditions, particularly to counteract global cooling.

5.2.1 Artificial Sequestration

One difficulty is that fossil fuel-generated energy is often required to carry out artificial sequestration, which generates more CO_2 and results in a lower net reduction. The costs of underground and oceanic injection (remedy C) appear to be higher than many of the other remedies. The costs of carbonate dissolution in seawater, one of the lesser-known options, may be lower than those shown if the CO_2 source is located on the ocean and there is a nearby source of limestone. Rau et al (2001) quote costs as low as $25-160 per ton carbon in these favorable circumstances. In those cases where concentrated CO_2 is sequestered it may be possible to release it fairly rapidly if global cooling threatened.

5.2.2 Enhancing Natural Sequestration

The costs of intensive forestry (remedy D) appear to be broadly similar but possibly higher than the “conventional” approaches. The approach offers very little flexibility to the extent that trees are involved because of their long life span, although it would presumably be possible to burn the trees if cooling threatened.

The costs of oceanic fertilization with phosphate on iron (remedy E) appear to be lower than GHG mitigation but still significant. The impacts on the plant and animal life of the oceans is an area of concern. And the reverse process of increasing atmospheric CO_2 levels in this way would appear to be difficult.

5.3 Engineered Climate Selection or Changing Earth’s Radiation Balance (R3)

A major advantage of options that change Earth’s radiation balance is that they would allow global temperatures to be changed in either direction and determined relatively precisely and independently of GHG levels. And this could be done without the necessity for individual decisions by individuals against their immediate self-interest. Global temperatures could be maintained at what may be determined to be optimum on the basis of other criteria while the economic advantages of higher than natural corresponding atmospheric CO_2 levels such as reduced control costs and increased growth of some plants, including most domesticated crops (Jablonski et al, 2002), are maintained. This has both good and bad results. It is good in that there would be no need to undertake expensive efforts to reduce GHG levels in terms of their climatological impacts. But it may have adverse effects because of other non-climate change impacts of elevated GHG concentrations, which would not be mitigated. The most important of these impacts so far identified appears to be the impact of elevated CO_2 concentrations on ocean acidification (Royal Society, 2005), which in time would likely have adverse effects on calcifying marine organisms (including corals).[26] The extent and importance of these effects would therefore appear to be an important research issue in judging between the alternatives.

5.3.1 Dispersing Sulfur Dioxide into the Stratosphere (Remedy F)

Based on observations of the climatic effects of adding volcanic sulfur to the stratosphere discussed in Section 2.8, remedy F, sulfate particles added to the stratosphere, would clearly be effective against global warming (but not cooling) given the previously noted widely accepted experience with the climatological results of major volcanic eruptions, but could possibly be risky in terms of unintended environmental effects on the stratosphere, especially the ozone layer. Wood (2005a) argues that particles would be emplaced well below the ozone layer and that there is only slow vertical mixing, but does advocate "real air" measurements. The importance of this option is that volcanic experience with this remedy has demonstrated the strong climatic effects that this remedy has.

5.3.2 Optimized Radiative Forcing Using the Stratosphere (Remedy G)

It is very reasonable to assume that humans could greatly improve on nature's efforts by optimizing this last approach (remedy F) to the problems of global warming and cooling. The Livermore papers discuss the use of specialized materials in the stratosphere and find these approaches to be much less expensive and more effective than the "conventional" approach of trying to adjust the emission rates of greenhouse gases. In fact, they state (Teller et al, 2002 and elsewhere) that under some approaches, the net costs of at least some of their approaches can be "strongly negative" (i.e., there would be no net costs, only benefits). This is because of benefits their approaches may provide in other areas, such as reduced exposure to ultra-violet radiation and thus a reduction in skin cancer, greatly increased plant growth and agricultural productivity made possible by higher CO_2 levels made possible by the decoupling of CO_2 levels from climate, and even (if desired) a changed distribution of the heat energy from the sun falling on various parts of the world so as to make it more even. One of the more important additional benefits would be the ability to respond rapidly and presumably effectively to unanticipated and undesired changes in global temperatures in either direction, such as may occur as a result of major volcanic eruptions. Remedy G analyzes the stratospheric approaches advanced in some of the recent Livermore papers. It is the only remedy analyzed here (other than H) that meets all of the criteria discussed in Section 4.1, including environmental effectiveness, and would appear, based on the claims of its proponents, to be one of the best remedies discussed in this paper even though they agree some research and development would be useful before it is actually implemented. It is particularly strong on the very important flexibility criterion as well as the economic ones. The only drawbacks appears to be that it does not address the adverse effects of elevated CO_2 levels on ocean acidification and could have possible adverse environmental impacts on the stratosphere. Although precise cost calculations are difficult to make, the equivalent cost per ton of carbon removed appear to be in the range of 2 to 10 cents compared to \$50 to \$400 for the more conventional approaches (see Table 2 and Figure 1). This estimate is based on costs presented by Wood (2005) and an assumed offset of 10 gigatons of carbon per year and appears to be consistent with Keith's (2001) estimate. Even if the costs are underestimated (as sometimes happens with new technological proposals) by one or even two orders of magnitude, the conclusions remain the same. According to its proponents, it meets the first aspect of the flexibility criterion by making possible timely adjustments of global temperatures to "fine tune" them towards any of the goals listed in Section 3.2. It would seem to have a better chance than any of the other options except remedy H to control abrupt climate changes if advance agreement is reached as to what is to be done under specified circumstances or if rapid agreement could be reached as to what is to be done under new circumstances. It meets the second aspect of the flexibility criterion concerning the ability to control both global warming and cooling. According to its proponents, it even meets the third aspect of the flexibility criterion concerning the ability (but not the necessity) to change the geographic distribution of global temperatures. The benefits and costs are assumed to be what the Livermore paper authors say they are, although they are very close to those provided by Keith (2000 and 2001). This may be a minor leap of faith since most of the Livermore papers are non-peer-reviewed literature, but does not alter the clear effectiveness of this general type of remedy demonstrated by the climatic effects of major volcanic eruptions. Nordhaus (1992) argues that several geoengineering options are so low cost that the costs can be ignored so that the net benefits are roughly equal to the benefits from global warming control. Presumably this would apply to this specific remedy although it is not specifically mentioned by Nordhaus. On this basis, the efficiency of this remedy would appear to be strongly positive.

Although the basic physical and engineering principles needed to implement remedy G appear to be on solid ground, there are many unanswered questions concerning whether this option really has been optimized, exactly how it would be implemented, exactly how much it would cost, and the nature and extent of non-global warming environmental effects that need to be answered before actual implementation could reasonably be undertaken. The proponents agree that some research and development would be useful before it is actually implemented. Teller et al. (1999) suggest additional research and development of about $100 million to further refine this remedy and examine side effects; their Tyndall 2004 presentation mentions about $1 billion. Several of the other “non-conventional” remedies would also require additional refinement, but remedy G might require more than most of the others given the numerous options and potential environmental risks that need more thorough exploration. The authors recommend a series of trials using scaled down quantities to make sure that their theoretical calculations hold up in the real world and that they have not overlooked some negative environmental effects. In the case of the stratospheric options, the effects of these small scale trials would be designed to dissipate within about five years if any should be detrimental as a result of the movement of the materials of concern down out of the stratosphere, so in the view of the proponents should not be considered as a permanent alteration of the stratosphere even at small scale. These trials would appear prudent and would hopefully alleviate possible concerns that this novel approach would prove overly risky as long as the approach could be abandoned when and if adverse new information is acquired. Wood (2005) lists some of the research that he recommends be undertaken.

If the research and development were successful and subsequently implemented, what this approach would do is to break the relationship between CO_2 levels and temperature. Humans could increase CO_2 levels substantially if that is otherwise the desired outcome without incurring most of the costs imposed by unwanted global warming. And if CO_2 gets too low and/or an ice age threatens, temperatures could be rapidly increased to avert it. But it would not decrease the non-temperature effects of increased CO_2 levels in the atmosphere, such as increased ocean acidification.

To date the principal scientific attack on the Livermore papers has come from Steven Schneider on the grounds that varying insolation and albedo would “mess up” everyone's local (micro-)climate.[27] The proponents believe that research reported in Govindasamy (2003) on this issue provides an adequate response to this question. This paper reported on detailed modeling and argued that the "deep modes" of the current climate system maintain at least meso-scale climates world-wide without significant alteration as the space- and time-averaged insolation is varied by a few percent in order to offset 2X or 4X increases in atmospheric CO_2. The proponents believe that Govindasamy (2003) shows that their remedies would provide reasonably good compensation for any global warming due to higher CO_2 levels. The proponents have tried to anticipate and answer many other potential criticisms of their proposals as well. A recent news report[28] provides some interesting insights into the motivation for the Livermore papers and the internal questioning, research such as that mentioned above, and ultimately agreement that went on within the Laboratory concerning these proposals.

5.3.3 Optimized Radiative Forcing Using Space-based Deflector (Remedy H)

A space-based deflector is likely to take substantially longer to put into place and be much more expensive than stratospheric particles, but just as effective in reducing incoming sunlight, much more permanent, more flexible, have less environmental side effects, and involve lower maintenance costs. Keith's (2001) estimate is that the equivalent cost per ton of carbon removed is 20 cents to $2, although there is no evidence that this is based on a careful engineering assessment of the problems involved. One of the more important additional benefits compared to Remedy G would be the ability to respond even more rapidly (presumably immediately if adequate planning and coordination were accomplished ahead of time and the system was planned with this in mind) to unanticipated changes in global temperatures, such as may occur as a result of major volcanic eruptions or abrupt climate changes. It presumably would also avoid most or all of the possible environmental side effects possibly resulting from placing particles in the stratosphere. But it would involve something beyond what has ever previously been accomplished, namely, to assemble and maintain a large structure far out in space. Despite the recent problems of the space shuttle, there are no obvious reasons that this could not be done, but it might well require significant time as well as technical and other resources to accomplish. Only a very careful engineering study could fully estimate the costs involved. Since it would also take much longer to design, transport, and build, one possibility might be to consider this as a possible longer term, more permanent solution that could be built during a period when optimized stratospheric particles are used to control global temperatures as an "interim" measure.

5.4 General Conclusions Concerning Alternatives for Controlling Climate Change

Geoengineering is more than a little controversial; the disparity in views is illustrated by the following:

> Schneider (2001) argues that although "adaptation alone may prove inadequate," he would "prefer to slowly decrease our economic dependence on carbon fuels rather than to try to counter the potential side effects with centuries of injecting sulphuric acid into the atmosphere or iron into the oceans. Laying stress instead on carbon management, with little manipulation of biogeochemical or energy fluxes in nature, is a much less risky prospect…."
>
> Michaelson (1998) argues that "the response to the claim that geoengineering 'just won't work' is to argue that such a claim is premature in practice and foolish in principle. Of course, the case for any new technology is 'uneasy,' and uncertainty will remain up until a geoengineering project is put into place, but such uncertainty is not sufficient reason to fail to initiate research now. Nor can we be daunted by the prospect of vast, unforeseen secondary consequences of tampering with the Earth's climate; again, it is too early to tell. Caution is wisdom--but inordinate skepticism flies in the face of a century of technological achievement."

Considering only temperature-related effects, it is hard to find anything to like about remedy B other than that it is already largely in place in terms of its structure, at least until 2012. As outlined in Section 3, continued substantial reliance on it is most likely to result in substantial global warming because of its ineffectiveness,[29] dependence on individuals making decisions against their own self-interest, and its potential effect of limiting efforts to find better alternatives. Remedy B also appears useless as a way to control global cooling. And the economic efficiency of this option appears to be strongly negative. The other potential remedies (other than A, no change) range somewhere between B and G in their attractiveness. Remedies E through H appear to offer positive efficiency and make lower demands on individuals for implementation, but have varying costs and environmental side effects. Option G appears to be equal to or better than all the other options under each criterion (although H offers lower environmental risks at potentially much higher costs in time and money), so would appear with one important footnote to be reasonably called a superior option for dealing with gradual global warming despite Schneider's reservations concerning geoengineering options. There are many unanswered implementation questions, however, concerning whether this option really has been optimized, exactly how it would be implemented, exactly how much it would cost, who would pay for it, and the nature and extent of non-global warming environmental effects that would need to be answered before actual implementation could reasonably be undertaken. But there would appear to be a case for undertaking an early but limited research and development effort to answer the geoengineering implementation questions *before* making large investments in any high-cost remedies that might be undertaken under the Kyoto Protocol approach. Remedy G can also be viewed as a rapidly implemented interim measure while longer-term CO_2 reducing remedies are put into place and become effective and as an emergency response measure in the case of rapid climate changes such as major volcanic eruptions.

Although there is less experience with using these options than with option B, the technical risks would appear controllable through careful experimentation. In the unlikely event that such experimentation should show that all the permutations of option G have significant environmental side effects, this would suggest the use of option H. Rejecting geoengineering approaches because of their remaining technical uncertainties or unfamiliarity, as Schneider appears to do, does not appear to be a conclusion based on careful analysis. The major footnote to this conclusion concerns mitigating the non-temperature effects of increases in GHG levels (Problem 2 as defined in Section 1.1), which the radiative forcing approaches would not affect, but which will be discussed in more detail in Section 5.6.2.

The experience to date with the Kyoto Protocol has not shown that that approach can be effective in significantly reducing the growth of GHG emissions or stabilizing atmospheric CO_2 levels. There would obviously be considerable difficulty in reaching an international agreement to undertake geoengineering not covered by the Kyoto Protocol, although the same would be true of follow-ons to the Protocol. The advantage of the geoengineering approaches, however, is that once agreed upon, there is no need for individual cooperation of most of Earth's energy-using population, as would be required for effective, worldwide energy conservation or other mitigation efforts on the scale that would be needed to bring CO_2 emission levels back to levels that would stabilize atmospheric levels at less than "dangerous" levels. And if (as seems almost certain) there are major volcanic eruptions that send material into the stratosphere or if there should be a collapse of the ocean conveyor belt or other abrupt or unforeseen climate changes, there would appear to be no other feasible remedy that could effectively mitigate these changes. Careful preparations for geoengineering approaches involving remedy G may be justifiable even if they are never used for reducing global warming as an insurance policy against abrupt adverse climate changes such as these.

Continued pursuit of only the Kyoto approach (remedy B) appears to be counterproductive given the implementation problems inherent in it. Unfortunately, an unintended consequence may be that to discourage consideration of more effective measures during the long period needed for the major deficiencies of remedy B to become evident to all. Thus although the Kyoto approach is strongly favored by many environmentalists, the net result of pursuing it alone may be to postpone effective action to control global warming for as long as it takes for the world to recognize that this approach is very unlikely to significantly decrease atmospheric GHG levels.

5.5 Other Management Approaches Besides the Kyoto Protocol

In Section 1.2 several other possible management tools besides the Kyoto Protocol were briefly listed. The question now is how the conclusions above might differ if these other management tools were used. The analysis appears to yield the following conclusions:

(MA1a) This management option involves purely voluntary efforts by individuals/corporations concerned enough to do something, either with or without public educational efforts to persuade them to do so. This presumably eliminates the potential political backlash from angry constituents whose GHG-producing activities would be reduced. It should also result in the use of relatively efficient control measures. Similarly, only those willing to be internationally less competitive would undertake such solutions, so that presumably would eliminate that as a political problem. Although such efforts are likely to have a positive effect and deserve to be encouraged, it appears unlikely that a purely voluntary effort will have a significant effect on one or more of the four problems since the effects are likely to be very small compared to what would be required to meet the UNFCCC goals as currently interpreted. Kyoto was undertaken in large part because of concern that purely voluntary actions would be unlikely to meet the UNFCCC goals. This seems unlikely to have changed.

(MA2b) If one or even a few local jurisdictions should decide to take a decentralized approach as a result of a political decision (such as has recently occurred in California and may occur in other "blue" states) or a judicial interpretation of the law (such as might or might not occur as a result of *Commonwealth of Massachusetts v. EPA*), the result might be progress in solving a small portion of the larger problem originating in that local jurisdiction or jurisdictions. Or if one or even a few nations decided to pursue an approach that was independent of those taken by any international body or uncoordinated with a group of nations with significant emissions, the same would appear to be the case for those nations. But except if only low cost solutions were imposed, or if the country/jurisdictions pursued one of the radiative forcing options (which appears highly unlikely in the case of local jurisdictions given that such efforts are likely to be necessarily based on existing national laws rather than new laws), the results would presumably be less efficient and effective than under the Kyoto management approach since the jurisdictions involved would presumably be the only ones to pursue this approach and would be limited to whatever control measures may be available under current national laws in the case of local jurisdictions. In the (unlikely) case of the radiative forcing options, a technologically advanced and wealthy country could indeed "go it alone" and institute a very effective and efficient solution but at the cost of possible condemnation by the rest of the world since the cost to that country would apparently be low. The costs would presumably be higher under non-radiative forcing solutions since a locally-based approach using existing law is likely to be less efficient than one based on new national legislation tailored to minimizing the costs of control for these particular pollutants (such as by the use of economic incentives such as cap and trade). This does not mean, of course, that decentralized decisions could not be used to "push" the political process at the national level by local jurisdictions by creating costly or otherwise unpalatable alternatives unless alternative political decisions were made at the national level.

(MA2c) One or more countries could adopt liability laws/legal precedents that make it very expensive for companies to sell/use very high GHG emitting products. The State of California, for example, has recently filed suit against the world's six largest automakers asking that they pay damages for the GHGs that their vehicles emit.[30] Unless all countries adopted them and had similarly effective legal institutions, the results would probably be worse than under the Kyoto scenario. Presumably only those countries with strong judicial systems, liability-based legal traditions, and strong motivation could effectively utilize this approach. In addition, such an approach is unlikely to result in the adoption of the lowest cost control options given that no one executive branch institution would coordinate the control efforts for that purpose. Finally, it is difficult to see how any of the lower cost radiative forcing options could be implemented under this approach. As in MA2c, however, it is entirely possible that climate change torts could be used to "encourage" the political process to take other actions to solve the problem. But if this process actually determined the control measures used, the results would probably be less efficient and effective than under the Kyoto approach.

(MA4) This option is a hypothetical new international approach utilizing the best of all the other management approaches and using all available technologies and including all sources of GHG emissions, but using a better rationale based on relative responsibility for the problem and the "polluter pays" principle. It would appear to be primarily useful if the world decides to make a serious effort to control ocean acidification since all the other problems can be more effectively and efficiently be controlled us-using MA3, engineered climate selection. One possibility would be the creation of an international fund based on past and present emissions.[31] This is intended as something of an "ideal" approach that solves some of the major problems of Kyoto while also providing an international framework for coordinated reductions in GHG emissions. The intention here is to fashion a replacement for Kyoto that corrects at least some of its major deficiencies, as discussed earlier in Section 3.3. The place to start would appear to be to correct the weak rationale for Kyoto. As outlined in Section 3.3.7, a much more logical basis for such an international agreement would be to base it on the "polluter pays" principle as opposed to the "rollback" approach with exemptions embodied in Kyoto. Those countries responsible for present and past GHG emissions would pay an amount based on the lesser of the damages these emissions have caused/will cause and the cost of solving the resulting problems.[32] Presumably some allowance could be arranged for countries to spend a portion of what they would owe internally for climate control purposes. Where the damages/costs for past and present emissions are roughly the same, as in the case of CO_2, the amount paid by paid by each country would presumably be proportional to their total anthropogenic emissions since human-caused emissions started causing problems. Where past emissions cause less damage/cost less to control than current emissions, the total amount paid by each country would be the sum of the damages/costs from past and from current emissions. These payments, in turn, would be used to provide incentives for the development and application of technology that reduces GHG emissions. Since all countries that have emitted GHGs that have not dissipated in not injurious ways would be obligated to pay, all such countries would have an incentive to reduce emissions. Although the payments would be mandatory, the emission decisions would be voluntary. In the case of CO_2, all emissions since atmospheric levels of CO_2 started to rise would be included since these emissions are still in the atmosphere or have been absorbed by the oceans, with a deleterious effect on ocean acidification. Such a fund could be used to pay for the least expensive and most effective remedies regardless of where they may occur and the technology used, including engineered climate selection, nuclear power, incentives to reduce CO_2 emissions from air travel, and public educational efforts where they are likely to be effective. It would appear important that this "ideal" successor to Kyoto be fully enforceable. One of the major design issues would presumably be how to establish fair and equitable payments for emissions. The ideal would be levels that would just accomplish the desired goals—say a limit of $2^{o}C$ on world temperature increases and a corresponding (but as yet not established) goal for limits on ocean acidification. If the temperature goals were to be achieved using stratospheric radiative forcing only, the fee levels would presumably be very low—probably so low that such a complicated agreement might not be worth pursuing. If, on the other hand, a serious effort were undertaken to prevent ocean acidification, much higher levels would be required. It would be important to allow some flexibility so that prices could be changed if goals were or were not being met. Such an approach would encourage an incentive approach rather than a coercive approach to climate change control. Individuals and nations could decide whether to burn and pay or use alternatives and not pay. They could also choose to accept financial assistance from the fund or not to.

It must be emphasized that such a new hypothetical proposal would not solve all the problems of Kyoto. The principal remaining difficulty would be the high cost of preventing ocean acidification and the reluctance of people and governments to paying that cost. But if the world wants to achieve that goal, this may offer a possible way forward towards that end that just might provide a basis on which the nations of the world could agree. All countries would be liable, but most (but not all) of the cost would still be paid by the developed world.

5.6 Conclusions with Respect to Specific Climate Change Problems

Section 5.4 summarized the general conclusions regarding efficiency and effectiveness of each remedy for the climate change problem as a whole. This section applies these conclusions to suggesting solutions for each of the four specific climate change problems delineated in Section 1.1 and Table 1.

5.6.1 Gradual Increase in Global Temperatures (Problem P1)

This corresponds to problem P1 in Section 1.1 and in Table 1. The general conclusions outlined in Section 5.4 apply to this problem without change, so that remedy G appears to be the superior option for dealing with this problem. Gradually increasing global warming could most efficiently and effectively be controlled using one of the radiative forcing remedies. Attempts to control it through greenhouse gas control are unlikely to be successful because of the lifestyle changes required and high cost of doing so. The principal result of efforts to do so may be to delay effective action. Radiative forcing remedies are some of the few realistic alternatives available. They could best be carried out on an internationally cooperative basis, but could also be done on a "go-it-alone" basis at the risk of possible international condemnation.

5.6.2 Non-temperature Effects of Higher Atmospheric GHG Levels (P2)

Some of these effects appear to be positive rather than negative; the positive ones actually favor the use of remedy G since they would not disturb the increasing atmospheric CO_2 levels. The primary example is the positive effect of elevated CO_2 levels on some plant growth. Presumably both those plants whose growth is stimulated by higher CO_2 concentrations as well as animals and humans who consume them will be better off by such higher concentrations. Current research suggests that cultivated crops and some weeds[33] may particularly benefit, perhaps at the expense of other plants that are not stimulated by higher CO_2 levels, however. The stimulation of cultivated crops should be a very major benefit to humans. The major adverse non-temperature-related effect of elevated GHG levels appears to be increased ocean acidification. Any of the remedies other than A, F, G, and H can be used to decrease/control the growth of atmospheric CO_2 levels and therefore ocean acidification. Remedy C, CO_2 sequestration, can also be used to directly remove CO_2 from the atmosphere. Other possibilities are to capture and use CO_2 for enhanced oil recovery and to add limestone or other alkaline minerals to streams of newly generated CO_2 or possibly directly to the oceans. Both of these can only be done in limited geographical settings, however. The Royal Society (2005) report argues that using limestone is infeasible on an oceanwide basis but does not comment on its use in CO_2 streams and does not provide cost estimates or other bases for judging this. There would therefore appear to be several questions needing answers: What would be the benefits gained from increased output of cultivated agriculture, what would be the costs of reducing CO_2 emissions into the atmosphere, and what would be the cost of neutralizing using limestone? Another question is whether the cheaper and more effective of these alternatives would be worth doing given what is likely to be a high cost in either case. Despite the efforts by the Royal Society (2005) to discuss remedies, we may still be in the early stages of analyzing what can and should be done about ocean acidification. Since all the current CO_2 mitigation strategies have been designed to treat problem P1, some effort is probably required to refine them for treating only ocean acidification. This problem is likely to be the most difficult of the four to solve, however, because of the potentially high cost, and may even be equally expensive as those for remedy B analyzed in this paper if CO_2 mitigation is the best available option and the benefits of reducing ocean acidification exceed the costs of doing so in this way.

If it is worthwhile from an economic viewpoint to control ocean acidification, it appears likely that the most effective remedies are those that can be implemented without the need for personal involvement in lifestyle decisions. That would suggest primarily remedy C, CO_2 sequestration. Obviously there are some (non-Kyoto) aspects of remedy B that do not involve personal involvement, like a possible decision to expand nuclear power, but which might prove to be deeply divisive politically. It is also likely to be higher cost and take longer to build than fossil fuel-derived power.

5.6.3 Potential for Triggering "Tipping Points"(P3)

It appears reasonable that the risks from "tipping points" or other abrupt climate changes may be proportional to global or regional temperature changes. The lower the increase in temperatures, the lower the chance that a "tipping point" will be hit. If global temperatures could be brought back to those typical for an interglacial period, presumably the chances would be even less. But conversely, any time that a higher "target" CO_2 level is adopted, the risk is presumably increased. Thus failure to actually achieve a given goal or target may carry with it an increased risk of abrupt climate change. The EU and others have decided that an increase of less than 2^oC does not carry with it significant risks, but there is no way to know whether this is actually the case without carrying out the experiment. It appears more plausible that there is rather increasing risk regardless of whether specific levels are exceeded. So if, for example, the Kyoto approach does not achieve a particular objective, there is likely to be some increase in the risk relative to the situation if it were met.

Since this paper has argued that the Kyoto approach is unlikely to meet many targets, it is important to ask which remedies may offer something useful if it becomes evident that a particular "trigger point" is about to be hit or an abrupt climate change is about to occur. In this case, only the radiative forcing remedies among those discussed in this paper might be implemented rapidly enough to control global temperatures and thereby avert the pending risk. There may also be imminent threats of a purely natural sort, and here too it would appear feasible to use radiative forcing remedies in a "rapid response" mode to greatly reduce these risks if advance preparations are in place. The issue here is the ability to react rapidly enough to increasing signs that a "tipping point" is approaching so as to avoid actually triggering it. All of the remedies have the potential to curb the gradual increase in temperatures, but only F, G, and H appear to have the flexibility to actually take evasive action if a "tipping point" should appear imminent. Because of its extreme flexibility, remedy H has perhaps the greatest potential, with remedy G next. It is important to note that these remedies would have to be "in place" and "ready to go" in order to be useful in most "rapid responses" such as envisioned in this paragraph and the next one, Section 5.6.4. Waiting until the need becomes evident to make these preparations would make an effective response more problematic. In the case of Remedy G, being in place and ready to go involves carrying out the needed further development work discussed in this paper, building international agreement as to how this remedy would be employed if needed, and arranging for the needed manufacturing and delivery means. In the case of Remedy H it would mean actually building the solar deflector and building a command and control capability to use it effectively. Remedies B through E have very little to nothing to offer with regard to this problem.

5.6.4 Short-term Cooling from Major Volcanic Eruptions (P4)

Because of the unexpected nature of such eruptions and the need to respond in a very short period of time if global cooling is to be avoided, only remedies G and H have the potential to play a useful role in responding them, with H probably more useful than G because of the possibly lower lag time required to move a deflector than to launch particles into the stratosphere. Depending on the particles used, there might also be conflict with the sulfur compounds emitted by the volcano involved.

5.7 Implications for the Choice of Remedies

There would appear to be two conclusions from this analysis:

● The participating Annex I nations appear to have selected one of the more difficult, expensive, and probably ineffective approaches (the Kyoto Protocol) to climate change control examined in this paper. If it could be fully and effectively implemented and expanded upon in future agreements, it might help to control ocean acidification (problem P2), but the available evidence indicates that all the other presently known climate change problems could be mitigated more rapidly, cheaply, efficiently, and effectively using engineered climate selection involving radiative forcing (remedy G or possibly F or H). Even if effectively implemented, Kyoto would not provide protection against global cooling from major volcanic eruptions (problem P4) or the ability to attempt to evade "tipping points" (P3) if not recognized decades in advance. Kyoto does appear to be more effective and efficient than most of the alternative management tools examined in Section 5.5 with the exception of a "go-it-alone" strategy involving radiative forcing.

● An efficient and effective solution would seem to be to actively pursue both geoengineering approaches involving radiative forcing as well as a new effort to reduce ocean acidification, with immediate priority given to the former in order to rapidly solve the potentially most critical problems. Although significant efforts would be needed to fine tune the proposals to implement these geoengineering approaches, build an international mechanism for making decisions, and to manufacture and launch the needed material/hardware, this approach could be used to rapidly reduce the risks from adverse feedback/tipping point problems from global warming and global cooling from major volcanic eruptions, and to rapidly stabilize global temperatures at any desired level. At the same time, the current global warming control effort could be refocused on the problem of reducing ocean acidification, with an early review of how acidification can best be mitigated and how the present international global warming reduction efforts could be modified to make them much more efficient and effective for this new (but probably closely related) purpose. The net result would be much earlier and more efficient control of three of the more detailed problems and at least the same progress (or lack thereof) in controlling ocean acidification as under the Kyoto approach. This would appear to provide significant gains and no losses compared to the Kyoto-only approach. This should also allow a little time for a new effort to better understand ocean acidification and design and carry out a careful program to reduce it directly, or possibly to decrease the CO_2 levels themselves to the extent that this is the most effective and lowest cost approach. If the latter, this should result in the lowest possible costs of carbon dioxide control by stretching out the period in which they would be made given the sensitivity of the costs of carbon dioxide emissions reductions to the rapidity with which they occur. Wigley (2006) provides some atmospheric modeling along these lines. It might also provide time to build a better replacement for Kyoto that remedies some of its most glaring problems.

The proposed priorities among the various remedies are shown in Table 1. The rationale is as follows. Remedy G appears to be very inexpensive and very effective in solving all the climate change problems other than ocean acidification very rapidly. So it is given the highest priority or 1. Reducing ocean acidification appears to be addressed most efficiently by using limestone to neutralize those streams of CO_2 near oceans and sources of limestone or to use it for advanced oil recovery. So remedy C is accorded the second highest priority or 2. If it appears efficient to further reduce ocean acidification, it would appear that the most effective remedies would involve CO_2 sequestration somewhere other than the ocean since this could be done without worldwide cooperation of the world's population. So still remedy C. If it appears efficient to go beyond what CO_2 sequestration can efficiently accomplish into other approaches that do involve worldwide public cooperation, that would presumably be accomplished under something similar to MA4. So it is accorded a priority of 3. Finally, for the reasons outlined in Section 5.3.3, there are some advantages of remedy H over remedy G. The only problems are the technological and other resources and the time that would be required to implement it. So presumably this should be a longer-term remedy that might usefully receive early research and engineering efforts but would not be implemented until more experience is gained with remedy G by actually trying to implement it. Hence this remedy is accorded a priority of 4.

From an economic viewpoint, whether ocean acidification reduction is worth pursuing beyond purely voluntary efforts would appear to be the most difficult analytical issue. An economic evaluation of the issue based on currently available information depends critically on the value of avoiding further ocean acidification offset by the value of the positive effects of CO_2 buildup in the atmosphere. The Royal Society report (2005) suggests that if the world follows a business-as-usual approach with regard to the buildup of CO_2 in the atmosphere the resulting ocean acidification would in time have very severe effects on the ocean ecosystem. This could indeed have very large damages to humans as well. Given the potentially very large cost of mitigating this effect, a greatly expanded research program would appear to be crucial to making an informed decision on whether and how rapidly to proceed with these very expensive CO_2 mitigation efforts. Assuming that a decision is made that CO_2 mitigation is worthwhile because of these effects, the inexpensive geoengineering approaches which would hopefully already be underway should prove to be a wise investment since they would reduce global warming until the ocean acidification mitigation efforts may be effective and provide an insurance policy against abrupt adverse climate changes in either direction such as those that will result from future major volcanic eruptions. Thus what have long been viewed as competitive solutions should better be regarded as complimentary solutions of a very complex environmental problem. In the case where a decision was made to proceed with conventional CO_2 emission reduction after remedy G had already been implemented, the relatively small added costs of remedy G would not be lost since all the problems except ocean acidification would have been addressed earlier and the added capability to address problems (3) and (4) would presumably have proved useful in themselves. It should be noted that without advance development, planning, international agreements, manufacturing, and delivery systems, remedies G and F could not fulfill these shorter-term climate control functions.

6. Likely Major Objections to Engineered Climate Selection

Assuming that any remaining technical problems in implementing optimized radiative forcing could be resolved through a proposed limited development program such as the proponents have proposed, the primary objections to engineered climate selection solutions are likely to be philosophical, legal, governmental, and strategic.[34]

6.1 Philosophical

The major argument is likely to be whether humans should take direct management responsibility for determining global temperatures. Although humans have been having an increasing effect on temperatures, it has been heretofore been left to nature rather than man to determine the outcome from this important aspect of the environment. The argument is likely to be that it is not acceptable to directly change nature by changing Earth’s radiation balance directly. It is acceptable to change it by decreasing GHG emissions but not by overt decisions. In other words, it has until recently been acceptable to increase GHG emissions as long as it is done for non-climatic reasons such as human gain or convenience and it was generally unknown what the effects would be, and it is all right to decrease GHG emissions to an earlier level since that is merely removing some of man's effects on the environment. But some may argue that it is not all right to deliberately remove GHGs already in the atmosphere or change Earth's radiation balance directly even though it would be for exactly the same purpose—to decrease global warming. That, it may be argued, would be interfering with "nature." A very good case, however, can be made that human-induced GHG releases and mitigation are already interfering with "nature," just in a less overt way. And directly managing global temperatures focuses attention on the environmentally important issue—the desired temperature regime for the Earth.

6.2 Legal

Attempts to use of engineered climate selection to "solve" the problem might run into the problem that much of the Western legal system assumes that there is no recovery for damages resulting from "acts of God." But if someone or some government deliberately alters Earth's radiation balance, even for a positive purpose, this may open the possibility that those responsible could be sued for damages by those who believe that damages they sustained from climate-related events were due to the actions of those who they believe attempted to alter nature. The most obvious solution to this problem would be a change in the law to either deny recovery of damages from the use of governmental engineered climate selection approaches to climatic temperature control or to make such liabilities fall onto governments, which would have to fund them out of taxes. This appears to be an area where legal inputs would be much needed.

6.3 Governmental

In a world of sovereign countries, an international process would need to be worked out to determine if, when, and how to deliberately alter global temperatures. This would have to include processes to determine when the results were unsatisfactory and how policy changes would be instituted to solve problems that might be encountered. Although this would not be without difficulty, it is hard to imagine that it would be more difficult than the negotiations that led to the Kyoto Protocol and would be needed if there are to be enforceable follow-on agreements, if such can even be accomplished. But once an agreement was reached, the actual implementation of such agreements would not depend on the cooperation of many governments and people, as is the case under Kyoto.

6.4 Strategic

There may be those who may oppose the proposal made in this paper on the grounds that if the gradual global warming problem is "solved" through engineered climate selction through radiative forcing then they will find it harder to persuade people to reduce fossil fuel use. The problem with this thinking is that it raises the question of whether the object is to solve environmental problems or to achieve some other objective. The position taken here is that the purpose should be to solve important environmental problems, and to do so in the most effective and efficient way available. Those who advocate a Kyoto-only approach are in great danger of achieving nothing and contributing to the increasing risks facing our planet at considerable risk from climate change in hopes of achieving a different objective. It appears better to separate the various problems—gradual global warming, ocean acidification, global warming tipping points, and global cooling from volcanic eruptions—and design a realistic program to tackle each one rather than risking everything for what some may regard as a single overall solution that appears unlikely to be achieved if pursued in this way.

7. Conclusions

This paper assumes that global climate change poses a major environmental problem--perhaps the most difficult one that the world has ever faced. For the purposes of this paper the climate change problem is defined as including four related problems: continued gradual global warming over the next few centuries, non-temperature-related adverse effects of increasing levels of greenhouse gases in the atmosphere such as ocean acidification, the potential effects of "tipping points" where warming may trigger particularly serious abrupt adverse effects, and shorter-term episodes of global cooling caused by volcanic eruptions. The paper asks how effective and efficient a variety of management approaches, particularly the Kyoto Protocol, would be in preventing or mitigating each of these problems, and whether there are alternative approaches that would be more so? The paper takes a very broad view of the problem by including the control of both long and short-term impacts of human activities and natural forces on global temperatures and greenhouse gas levels since it is only by looking at all the major aspects of the problem that effective and efficient solutions can meaningfully be discussed.

The paper concludes that the Protocol will certainly not prevent either global warming or cooling, and that it is unlikely that the mitigation of global warming will meet European Union interpretations of the meaning of the UN goals for maximum temperature increases. If fully implemented, it would probably result in minor decreases in the temperature rise that would otherwise occur and would not provide any capability to respond to global cooling. One of the fundamental problems is that in order for a Kyoto-type approach to achieve the UN goals as defined by the European Union would require the cooperation and participation of most of the world's governments and population to restrict energy use in ways that would directly reduce their welfare but does not provide effective incentives/penalties to bring about such cooperation and participation. It is difficult to see why politicians would be willing to force their constituents to adopt unpopular and expensive constraints on their activities or why many of their constituents would not pursue every available loophole or other avenues to avoid observing the constraints that are imposed. It appears unlikely that possible Kyoto follow-on agreements could overcome these implementation problems. In addition to being very difficult to implement, the mitigation likely to be undertaken under the Kyoto approach appears to be economically inefficient, very expensive if it were to have a major impact on global temperatures, and particularly unsuited to affecting global temperatures rapidly or flexibly. Trying to use it in this way to rapidly decrease global warming would be even more expensive because of the resulting expense of replacing greenhouse gas emitting equipment early in its life cycle. Continued pursuit of the Kyoto-only approach appears to be counterproductive given the implementation problems inherent in it. Unfortunately, the principal result of pursuing this approach is likely to be to prevent serious consideration of more effective measures during the long period needed for the major deficiencies of this approach to become evident to all as greenhouse gas emissions increase upward and shorter-term climate change problems are not effectively addressed.

Given these very serious problems with the Kyoto approach, the paper then asks if there are some other superior management and technological alternatives for controlling climate change; the paper reviews a wide array of control options using economic efficiency and other relevant criteria. It concludes that there appear to be superior alternatives involving radiative forcing that appear to be technically sound, would allow continued growth of fossil fuel use, very dramatically lower control costs, be economically efficient, avoid the need for individual actions to reduce greenhouse gas emissions, and permit relatively precise, rapid, and flexible adjustment of global temperatures, but would not affect non-temperature-related adverse effects of greenhouse gases, of which the most serious appears to be ocean acidification.

With this as background, the paper then extends the analysis to the four more detailed climate change problems:

(P1) **Gradually increasing global warming** could most efficiently, effectively, and rapidly be controlled using some of the more interesting radiative forcing or engineered climate selection remedies. Attempts to control it through greenhouse gas control under the Kyoto Protocol in particular are likely to be largely unsuccessful in terms of meeting current interpretations of its goals and very slow because of its unenforceability, the worldwide cooperation and personal lifestyle changes required, and the high cost of meeting goals that would actually make a significant difference. Other management approaches based on disaggregated, local, or voluntary controls, or liability for emissions would probably be even less successful and efficient. However well intentioned and helpful they may be if they reduce less-expensive-to-control emissions, there is also a danger that they will end up delaying effective action by providing a false hope that they will solve the problem. Radiative forcing remedies are some of the few realistic alternatives available to meet the goals. They could best be carried out on an internationally cooperative basis, but could also be done on a "go-it-alone" basis at the risk of possible international condemnation.

(P2) **The non-temperature-related effects of increasing greenhouse gases in the atmosphere** are both positive and negative. The major positive effects of carbon dioxide (on plant growth) would be lost if atmospheric levels were returned to "normal" levels. The most serious negative problem appears to be ocean acidification, but is not well understood as yet. The principal choices for dealing with this problem appear to be using limestone to neutralize streams of newly generated carbon dioxide in advantageous circumstances, sequestering it, and reducing atmospheric carbon dioxide emissions, in that order of decreasing likely effectiveness and increasing cost.

(P3) It appears likely that the **risks from "tipping points" or abrupt climate changes** would be reduced to the extent that atmospheric GHG levels or global temperatures were reduced. But if, as also appears likely, atmospheric GHG levels are not rapidly reduced to "normal" levels, the radiative forcing remedies could be used to directly control global temperatures and thereby greatly reduce these risks; if imminent dangers should threaten, it appears feasible to use some radiative forcing remedies in a "rapid response" mode to greatly reduce these risks *if advance preparations are in place to do so*.

(P4) **Shorter-term episodes of global cooling from major volcanic eruptions** are a certain and possibly even a catastrophic risk, and can *only* be addressed through radiative forcing approaches among the remedies reviewed in this paper. Advance preparations would again be required.

An effective and efficient solution would seem to be to actively pursue a combination approach involving both engineered climate selection using radiative forcing by means of stratospheric particles optimized for this purpose as well as a new effort to reduce ocean acidification, with immediate priority given to the former in order to solve all the non-ocean acidification problems quickly while the more difficult, much slower, and much more costly effort to reduce ocean acidification is undertaken and carried out. Although significant effort would be required to fine tune the proposals to implement these engineered climate selection approaches, build an international mechanism for making decisions, and to manufacture and launch the needed material/hardware, this approach could be used to rapidly reduce the risks from adverse feedback/tipping point problems from global warming and from global cooling from major volcanic eruptions, and to rapidly stabilize global temperatures at any desired level. This should also allow some time to design and carry out a careful program to reduce ocean acidification, or possibly to decrease the CO_2 levels themselves if this proves to be worthwhile and the best approach. If the latter, this should result in the lowest possible costs of carbon dioxide control by stretching out the period in which they would be made given the sensitivity of the costs of carbon dioxide emissions reductions to the rapidity with which they occur. Substituting lower emission technology will be much cheaper if the goods in which it is embedded need to be replaced anyway because of old age or technological obsolescence.

A useful early task would seem to be a review of how acidification can best be mitigated and how the present international global warming reduction efforts could be modified to make them much more efficient and effective for this new (but possibly closely related) purpose. The net result would be much earlier and more efficient control of three of the more detailed problems and no less progress in controlling ocean acidification than under the Kyoto approach. This would appear to provide a very useful and necessary insurance policy against future major climate problems on Earth.

Thus what have sometimes been viewed as competitive solutions should better be regarded as complimentary solutions of an important set of separable but inter-related environmental problems. Several management approaches other than Kyoto are discussed, but are found to be inferior to it except in the case of an “ideal” replacement for Kyoto and radiative forcing, which could be effectively implemented by one country with sufficient technological talent and resources, but at the cost of possible international condemnation.

The paper also reviews several other management approaches involving voluntary efforts, government-determined de-carbonization to reduce global warming problems including decentralized decision-making and liability-based efforts to decrease GHG levels in the atmosphere, and a new approach involving use of all available technologies. It finds that the voluntary and the currently discussed government-determined de-carbonization possibilities are likely to be less effective and efficient than the Kyoto approach. It does suggest a replacement for Kyoto, however, which would correct a number of the deficiencies of Kyoto.

It appears likely that if the world follows Kyoto or any of the other government-determined de-carbonization approaches considered in this paper, both global temperatures and atmospheric carbon dioxide levels will continue to increase at roughly current rates. At some point in the future this may well become all too evident and engineered climate selection may be reconsidered. It would seem far better, however, not to wait until happens before using engineered climate selection since there would be reduced risks of hitting a tipping point, the possibility of warding off abrupt climate changes, protection from volcanic cooling/winters, and avoidance of various climate-induced unpleasantries in the meantime.

Finally, the paper discusses four of the primary impediments to the use of engineered climate selection approaches. Although these impediments are significant, the paper argues that they are easier to solve than the already evident problems surrounding the Kyoto approach.

References

Aldy, Joseph E., Scott Barrett, Robert N. Stavins, 2003. In "Thirteen Plus One: A Comparison of Global Climate Policy Architectures," *Climate Policy*, 3(4), December, pp. 373-97.

Allenby, Braden R., 2003 "Global Climate Change and Anthropogenic Earth," Introduction to *The Carbon Dioxide Dilemma: Promising Technologies and Policies,* National Academy of Engineering, National Research Council, Washington, DC. Also available at: http://darwin.nap.edu/execsumm_pdf/10798.pdf

Alley, Richard B., 2000, *Two-Mile Time Machine: Ice Cores, Abrupt Climate Change, and Our Future,* Princeton University Press**.**

Alley, R. B., J. Marotzke, W. D. Nordhaus, J. T. Overpeck, D. M. Peteet, R. A. Pielke Jr., R. T. Pierrehumbert, P. B. Rhines, T. F. Stocker, L. D. Talley, and J. M. Wallace, 2003, "Abrupt Climate Change," *Science*, March 23, pp. 2005-10.

Ambrose, Stanley H., 1998, "Late Pleistocene Human Population Bottlenecks, Volcanic Winter, and Differentiation of Modern Humans," *Journal of Human Evolution*, Vol. 34, pp. 623-51. Partial extracts available at http://www.bradshawfoundation.com/evolution/

Bala, Govindasamy, Arthur Mirin, Michael Wickett, and Christine Delire, 2005, "Multicentury Changes to the Global Climate and Carbon Cycle: Results from a Coupled Climate and Carbon Cycle Model," *Journal of Climate*, Volume 18, Number 20, November 2005, pp. 4531–44.

Barrett, Scott, and Robert Stavins, "Increasing Participation and Compliance in International climate Change Agreements," 2003, *International Environmental Agreements: Politics, Law and Economics*, Vol. 3, pp. 349-76. Also available from http://www.ksg.harvard.edu/cbg/eephu/barrett_stavins.pdf

Baumert, Kevin A., ed., 2002, *Building on the Kyoto Protocol: Options for Protecting the Climate*, World Resources Institute, Washington, DC. Available at http://216.239.51.104/search?q=cache:8cbxCiAYVi4J:climate.wri.org/pubs_pdf.cfm%3FPubID%3D3762+%22Options+for+protecting+the+climate%22+Baumert+pdf&hl=en&gl=us&ct=clnk&cd=1

Bindeman, Ilya N., 2006, "The Secrets of Supervolcanoes," *Scientific American*, May 22. Available at http://www.scientificamerican.com/print_version.cfm?articleID=0006E0BF-BB43-146C-BB4383414B7F0000

Bongaarts, John, "Population Growth and Global Warming," National Council for Science and the Environment, Washington, DC, http://www.cnie.org/pop/bongaarts/popgrowth/b.htm

Breiterman, Charles, "Ice Ages and the Earth's Climate." In *Considering the Earth as an Open System*, http://jesse.usra.edu/articles/breiterman/breiterman-06.html

Broecker, W.S., 1997, “Thermohaline circulation, the Achilles Heel of our climate system: Will man-made CO_2 upset the current balance?” *Science,* Vol. 278, pp. 1582-1588.

Bryden, H., H. Longwort H., and S. Cunningham, 2005, “Atlantic currents show signs of weakening,” *Nature*, Vol. 438, pp. 665-7.

Caldeira, Ken, Atul K. Jain, and Martin L. Hoffert, 2003. In “Climate Sensitivity Uncertainty and the Need for Energy Without CO_2 Emission,” *Science*, Vol. 299, March 28, pp. 2052-4.

Cruzen, P. J., 2006, “Albedo enhancement by stratospheric sulfur injections: a contribution to resolve a policy dilemma?” *Climatic Change,* August.

Deutch, John M., and Ernest J.Moniz, 2006, “The Nuclear Option,” *Scientific American*, Vol. 295, No. 3, September, pp. 76-83.

de Silva, Shanaka L., “Volcanic Eruptions and Their Impact on the Earth’s Climate,” in J. Oliver (ed.), *Encyclopaedia of World Climate.* Springer, pp. 788 - 794. Also available at http://www.space.edu/documents/Volcanoclimate.pdf

Dyson, F. J. and G. Marland, 1979, “Technical Fixes for the climatic effects of CO_2,” *Workshop on the Global Effects of Carbon Dioxide from Fossil Fuels*, Report CONF-770385, US Department of Energy, Washington, DC.

Edenhofer, Ottmar, Carlo Carraro, Jonathan Kohler, and Michael Grubb, editors, 2006, *Endogenous Technological Change and the Economics of Atmospheric Stabilization*, a Special Issue of the *Energy Journal.*

Fischer, Carolyn, and Richard D. Morgenstern, 2005, “Carbon Abatement Costs: Why the Range of Estimates?” Resources for the Future Discussion Paper 03-42 Rev., November. Available at http://www.rff.org/rff/Documents/RFF-DP-03-42-REV.pdf

Govindasamy, B., K. Caldeira, and P.B. Duffy, 2003. In “Geoengineering Earth's radiation balance to mitigate climate change from a quadrupling of $CO_{2,}$,” *Global and Planetary Change* 37, pp.157-168. Also available from http://eed.llnl.gov/cccm/pdf/Govindasamy_etal_2003.pdf

Hare, Bill, and Malte Meinshausen, 2004, *How Much Warming Are We Committed to and How Much Can Be Avoided*, Report No. 93, Potsdam Institute for Climate Impact Research. Available from
http://www.pik-potsdam.de/pik_web/publications/pik_reports/reports/pr.93/pr93.pdf

Hoffert, Martin I., Ken Caldeira, Gregory Benford, David R. Criswell, Christopher Green, Howard Herzog, Atul K Jain, Haroon S. Kheshgi, Klaus S. Lackner, John S. Lewis, H. Douglas Lightfoot, Wallace Manheimer, John C. Mankins, Michael E. Mauel, L. John Perkins, Michael E. Schlesinger, Tyler Volk, and Tom M. L. Wigley, 2002. In ‘Advanced Technology Paths to Global Climate Stability: Energy for a Greenhouse Planet,’ *Science*, Vol. 298, November 1, 981-7.

Intergovernmental Panel on Climate Change (IPCC), 2001, Working Group III, *Summary for Policymakers: Climate Change 2001: Mitigation*.

Intergovernmental Panel on Climate Change (IPCC), 2005, *Carbon Dioxide Capture and Storage: Summary for Policymakers*, September. Available at http://arch.rivm.nl/env/int/ipcc/pages_media/SRCCS-final/ccsspm.pdf

Jablonski, Leanne M., Xianzhong Wang, and Peter S. Curtis, 2002, "Plant reproduction under Elevated CO_2 Conditions: a Meta-analysis of Reports on 79 Crop and Wild Species," *New Phytologist*, Vol. 156, October, p. 9.

Keith, David W., 2000. In "Geoengineering the Climate: History and Prospect," *Annual Rev. Energy Environ.*, Volume 25, pp. 245-84. Also available from: http://www.ucalgary.ca/~keith/papers/26.Keith.2000.GeoengineeringHistoryandProspect.e.pdf

Keith, David W., 2001, "Geoengineering and Carbon Management: Is There a Meaningful Distinction?" In D. Williams, B. Durie, P. McMullan, C. Paulson and A. Smith, eds, *Greenhouse Gas Control Technologies: Proceedings of the 5th International Conference*. CSIRO Publishing, Collingwood, Australia, pp. 1192-1197. Available from http://www.ucalgary.ca/~keith/papers/41.Keith.2001.GeogineeeringAndCarbonManagment.f.pdf

Kolstad, Charles D., and Michael Toman, 2001, "The Economics of Climate Policy," Discussion Paper 00-40REV, Resources for the Future, June. Available at: http://www.rff.org/rff/Documents/RFF-DP-00-40.pdf

Lane, Lee, 2006, "Reflections on Transatlantic Climate Policy," in *Proceedings of the Symposium on "Climate Policy in the Coming Phases of the Kyoto Process: Targets, Instruments, and the Role of Cap and Trade Schemes*, Brussels, February 20-21. Will be available at http://www.european-climate-forum.net/events/brussels2006/pdf/Lane.pdf (in preparation).

Lasky, Mark, 2003, "The Economic Costs of Reducing Emissions of Greenhouse Gases: A Survey of Economic Models," Technical Paper 2003-3, US Congressional Budget Office, May. Available at http://www.cbo.gov/ftpdocs/41xx/doc4198/2003-3.pdf

Livermore papers: This is the collective name given to Teller and Wood (1997), Teller et al (1999), Teller et al (2002), Wood (2005), Wood (2005a), and Wood's presentation in Tyndall Centre (2004).

Lovelock, James, 2006, *The Revenge of Gaia: Earth's Climate History and the Fate of Humanity*, Basic Books, New York.

Manne, Alan S., and Richard G. Richels, 1992, *Buying Greenhouse Insurance: The Economic Costs of CO_2 Emissions Limits,*" MIT Press.

McGuire, Bill, 2002, *A Guide to the End of the World: Everything You Never Wanted to Know*, Oxford University Press, Oxford, England.

Michaelson, Jay, 1998, “Geoengineering: A Climate Change Manhattan Project,” *Stanford Environmental Law Journal,* January. Also available from http://www.metatronics.net/lit/geo2.html

NAS, 1992. Panel on Policy Implications of Greenhouse Warming, *Policy Implications of Greenhouse Warming*, *Mitigation, Adaptation, and the Science Base*, U.S. National Academy of Sciences, National Academy Press, Washington DC.

Nordhaus, William, 1992, “An Optimal Transition Path for Controlling Greenhouse Gases,” *Science*, Vol. 258, November 20, pp. 1315-9. Available from: http://cowles.econ.yale.edu/P/cp/p08a/p0829.pdf

Nordhaus, William and Joseph G. Boyer, 1999, “Requiem for Kyoto: An Economic Analysis of the Kyoto Protocol,” February 8. Available from http://www.econ.yale.edu/~nordhaus/homepage/Kyoto.pdf

Olmstead, Sheila M., and Robert N. Stavins, 2006, “An International Policy Architecture for the Post-Kyoto Era, *American Economic Review Papers and Proceedings*, May (forthcoming). Available at http://ksghome.harvard.edu/~rstavins/Papers/Olmstead & Stavins Paper for Distribution.pdf

Pacala, S., and R. Socolow, 2004, “Solving the Climate Problem for the Next 50 Years with Current Technologies,” *Science*, Vol. 305, pp. 968-72, August 13.

Posner, Richard A., 2004, *Catastrophe: Risk and Response*, Oxford University Press, New York.

Rau, Greg H., Ken Caldeira, Kevin G. Knauss, Bill Downs, and Hamid Sarv, 2001, “Enhanced Enhanced Carbonate Dissolution as a Means of Capturing and Sequestering Carbon Dioxide,” First National Conference on Carbon Sequestration, Washington, DC, May 14-17. Available at http://www.netl.doe.gov/publications/proceedings/01/carbon_seq/p24.pdf

Robock, Alan, 2002, “Volcanic Eruptions,” in Volume I, *The Earth system: physical and chemical dimensions of global environmental change*, pp. 738-44, in the *Encyclopedia of Global Environmental Change*, John Wiley and Sons, Chichester. Available at http://climate.envsci.rutgers.edu/pdf/EGECVolcanicEruptions.pdf

Royal Society, 2005, *Ocean Acidification Due to Increasing Atmospheric Carbon Dioxide*, Policy Document 12/05, London, June. Available at http://www.royalsoc.ac.uk/displaypagedoc.asp?id=13539

Ruddiman, William F., 2003, “The Anthropogenic Greenhouse Era Began Thousands of Years Ago,” *Climatic Change*, December, pp. 261-93.

Ruddiman, W.F., 2005 “Cold Climate During the Closest Stage 11 Analog to Recent Millennia,” *Quaternary Science Reviews*, Volume 24, June-July, pp. 1111-21.

Ruddiman, William F., 2005a, *Plows, Plagues, and Petroleum*, Princeton University Press.

Schneider, Stephen H., 2001, "Earth Systems Engineering and Management," *Nature*, Vol. 409, January, pp. 417-21.

Schellnhuber, Hans Joachim, editor, 2006, *Avoiding Dangerous Climate Change*, Cambridge University Press. Available at http://www.defra.gov.uk/environment/climatechange/internat/pdf/avoid-dangercc.pdf
Shinnar, Reuel, and Francesco Citro, 2006, "A Road Map to U.S. Decarbonization," *Science*, Vol. 313, September 1, pp. 1243-4.

Siegenthaler, Urs, Thomas F. Stocker, Eric Monnin, Dieter Luthi, Jakob Schwander, Bernhard Stauffer, Dominique Raynaud, Jean-Marc Barnola, Hubertus Fischer, Valerie Masson-Delmotte, and Jean Jouzel, 2005, "Stable Carbon Cycle—Climate Relationship during the Late Pleistocene," *Science*, Vol. 310, November 25, pp. 1313-7.

Socolow, Robert, 2005, "Stabilization Wedges: Mitigation Tools for the Next Half Century," presentation at a symposium on "Avoiding Dangerous Climate Change" at Met Office, Exeter, England, February 3. Available at http://www.stabilisation2005.com/day3/Socolow.pdf

Stanhill, G., and S. Cohen, 2001, "Global Dimming: A Review of the Evidence," *Agricultural and Forest Meteorology,* Vol. 107, pp. 255-278

Teller, E., R. Hyde, and L. Wood, 1997, "Global Warming and Ice Ages: I. Prospects for Physics-Based Modulation of Global Change," Paper prepared for 22nd International Seminar on Planetary Emergencies, Erice, Italy, August 15. University of California Lawrence Livermore National Laboratory, Preprint UCRL-JC-128715. Available from http://www.llnl.gov/global-warm/231636.pdf

Teller, E., K. Caldeira, G. Canavan, B. Govindasamy, A. Grossman, R. Hyde, M. Ishikawa, A. Ledebuhr, C. Leith, C. Molenkamp, J. Nuckolls, and L. Wood, 1999, "Long-Range Weather Prediction and Prevention of Climate Catastrophes: A Status Report," Paper prepared for 24th International Seminar on Planetary Emergencies, Erice, Italy, August 18, University of California Lawrence Livermore National Laboratory Preprint UCRL-JC-135414. Available from http://www.llnl.gov/tid/lof/documents/pdf/236324.pdf

Teller, E., R. Hyde, and L. Wood, 2002, "Active Climate Stabilization: Practical Physics-Based Approaches to Prevention of Climate Change," National Academy of Engineering Symposium, Washington, DC, April 19, University of California Lawrence Livermore Laboratory Preprint UCRL-JC-148012. Available from http://www.llnl.gov/global-warm/148012.pdf

Tol, Richard S.J., 2003, "The Marginal Costs of Carbon Dioxide Emissions," paper presented at an International Symposium on the Social Cost of Carbon, July 7. Available from http://www.defra.gov.uk/environment/climatechange/carboncost/pdf/tol.pdf

Tol, Richard H. J., and Roda Verheyen, 2004, "State responsibility and compensation for climate change damages—a legal and economic assessment," *Energy Policy*, Vol. 32, pp. 1109-304.

Tyndall Centre and Cambridge-MIT Institute, 2004. Symposium on Macro-Engineering Options for Climate Change Management and Mitigation, January 7-9, Cambridge, England, http://www.tyndall.ac.uk/events/past_events/cmi.shtml

US Department of Energy (USDOE), Energy Information Administration, 2005, *International Energy Outlook 2005*, Washington, DC; available at http://www.stat-usa.gov/miscfiles.nsf/85e140505600107b852566490063411d/2981f0f832d84d3a85257157006fac0f/$FILE/IEO2005_ch002.pdf - search=%22Energy%20Information%20Adminis

US Department of Energy (USDOE), Energy Information Administration, 2006, *International Energy Outlook 2006* Washington, DC; available at http://www.eia.doe.gov/oiaf/ieo/index.html

Viner, David, and Phil Jones, 2000, "13: Volcanoes and Their Effect on Climate," Climate Research Unit, School of Environmental Sciences, University of East Anglia, Norwich, United Kingdom. Available from http://www.cru.uea.ac.uk/cru/info/volcano/

Walter, K. M., S. A. Zimov, J. P. Chanton, D. Verbyla, and F. S. Chapin, 2006, "Methane Bubbling from Siberian Thaw Lakes as a Positive Feedback to Climate Warming," *Nature*, Vol. 443, September 7.

Ward, Peter D., 2006, "Impact from the Deep," *Scientific American*, October, pp. 65-72.

Weber, Elke U., 2006, "Experience-based and Description-based Perception of Long-Term Risk: Why Global Warming Does Not Scare Us (Yet)," *Climatic Change* (forthcoming).

Wigley, T.M.L., 2006, "A Combined Mitigation/Geoengineering Approach to Climate Stabilization," *Sciencexpress*, September 14; available at http://www.sciencexpress.com

Wood, Lowell, 2005, "Earth Albedo Engineering," presentation to Energy and Engineering Study Group, Lawrence Livermore National Laboratory, April 7.

Wood, Lowell, 2005a, "Geoengineering: Albedo Modulation Approaches to Preferred Climates as the Atmospheric CO_2 Level Rises towards the 'Agricultural Optimum,'" Energy Modeling Forum's Workshop on Critical Issues in Climate Change, Snowmass, CO, July 26 to August 4.

Zimov, Sergey A., Edward A. G. Schuur, and F. Stuart Chapin III, 2006, "Permafrost and the Global Carbon Budget," *Science*, Vol. 312, pp. 1612-3, June 16.

Table 1: Usefulness of Some Climate Change Control Options in Solving Detailed Climate Change Problems

Problems/ Remedies	(P1) Gradual Global Warming	(P2) Ocean Acidification	(P3) Risks from "Tipping Points"	(P4) Risks of Short-term Cooling from Volcanic Eruptions	Proposed Priority
B. Conventional under Kyoto Protocol	Effective if ever achieved, which is very unlikely; high cost; very slow results	Effective if ever achieved; high cost	Vary with temperatures. Useless as a rapid response to imminent threats and to cooling	Useless	3
C. Artificial CO_2 sequestration/ neutralization	Effective but high cost except possibly neutralization in ideal cases	Effective but high cost except some neutralization	Probably useless except for increasing temperatures by releasing concentrated CO_2	Where CO_2 is in concentrated form, it could be released if cooling threatened	2
G. Optimized particles in stratosphere	Effective immediately; lowest cost	No effect	Can be quickly reduced with temperatures and also used for fairly rapid response	Effective as soon as particles are distributed unless there are interactions with volcanic emissions	1
H. Deflector in space	Effective if and when built; probably much higher cost than G	No effect	Can be quickly reduced and also used as an even more rapid response	Effective and more flexible if and when built than G	4

The problem numbers refer to those listed in Section 1.1. The control options are identified by letters corresponding to the row numbers in Table 2 and the remedy letters used in Sections 4 and 5. See Section 5.7 of the text for an explanation of the proposed priorities.
Prepared by Alan Carlin based on Table 2 and text.

Table 2: Evaluation of Some Alternative Approaches for Controlling Global Climate Change

Criteria Remedies	1.Effective Environ. Outcome	2.Dynamic Efficiency	3.Cost effectiveness	3a. Cost of Control[a]	4.Distributional Equity	5.Flexibility	5a. Alter Pace	5b. Global Cooling	5c. Temp. Redistribution	6.Participation & Compliance	7.Other Environmental Risks	8.Additional Considerations
R1/A. No intentional climate change control (business as usual)	Very low—depends on “dumb luck” to muddle through	Base case; not optimal due to high cost of climate change	No costs involved	DNA[b]	Costs of warming may be greatest for those near sea level including low-lying LDCs	Little desired or likely	DNA	DNA	DNA	None needed	None	Included as base case

R2/B. “Conventional” de-carbonization technologies selected by each country under Kyoto Protocol	Low given limited mitigation goals, short-term commitments, long response times, and limited incentives	Strongly negative since lower bound costs are higher than climate change benefits of perhaps $15 per ton (see text)	Low compared to some technological approaches	50-400[ac] Estimated marginal cost to achieve UNFCCC goals as interpreted by EU	Only industrial countries face targets but LDCs help shape rules. LDCs receive some adaptation assistance	Emission ceilings locked in but only for 5 years; climate response very slow	Possible but very difficult	No	No	Incentives very weak; requires massive international cooperation & bureaucratic effort; enforcement unlikely	None known	Protocol already in place calling for reducetions by some countries; reductions in oil use decrease national security risks
(R2a) Non-conventional de-carbonization or sequestration												

C. CO$_2$ artificial sequestration using injection into ocean or underground or neutralization	Medium-high if carried out on massive scale	Strongly negative	Very low	50-150;[d] 60-300[h] for CCS underground; 80-400[h] for ocean injection	Implementation costs borne by initiators; benefits and other possible costs borne by all	Could be halted rapidly, but increase in pace could only be done slowly	Yes	Presumably possible to remove CO$_2$ if concentrated	No	Int'l cooperation desirable for siting purposes	Probably low risk except for ocean injection, which could contribute to ocean acidification. Potential leakage problems for underground	Some experience with old oil and gas fields; possible NIMBY problems elsewhere
D. Intensive forestry to capture carbon in harvested trees	Low because of uncertainty about rate of accumulation	Likely to be negative but some projects could be positive	Low	10-100[d]	Implementation costs borne by initiators; benefits and other possible costs borne by all	Almost no flexibility because of time required to stop, start, or harvest trees	Only very slowly	Could remove trees and burn them	No	Cooperation and approval of landowners and probably governments required	Low risk; intensive cultivation will impact soils and biodiversity	Political issues: who pays costs; whose land is used?

E. Ocean fertilization with phosphate/iron	Medium--significant technical uncertainties	Probably somewhat positive	Medium	1-10[d]	Implementation costs borne by initiators; benefits and other possible costs borne by all	Medium to control warming but difficult to reverse once the carbon is on the sea floor	Yes	No	No	Int'l cooperation desirable for siting purposes	Probably high risk: Oxygen depletion resulting in methane release; change in ocean biota	Possible liability and other legal concerns
R3. Engineered climate selection												
F. Sulfur-containing particles added to stratosphere to control global warming	Very high; proven by major volcanic eruptions	Strongly positive; CO_2 increases would also aid agriculture	Very high for cooling purposes	<<1[d]	Probably fairer.[e] Implementation costs borne by initiators; benefits and other possible costs by all	High at least to control warming. Changes depend on residence time in stratosphere	Intensify rapidly; 5 year lag to decrease intensity	Not without changing substance used	Possible but only to cool	Not required once remedy agreed on	High--possible adverse interactions with other stratospheric species; sky whitening	Possible liability if disasters can be shown to result; no ocean acidification mitigation

G. Optimized radiative forcing by injecting specialized substances in stratosphere, e.g., see endnote 22	Very high based on (F) but unproven in real world trials with specified particles	Strongly positive for warming. Other benefits, e.g., UV protection, plant growth, offset volcanic eruption	Very high for both heating and cooling	<<1[f], or, at the risk of trying to be too precise, 0.02 to 0.1[g]	Probably fairer;[5] implementation costs borne by initiators; benefits and other possible costs received/ borne by all	High for both warming and cooling. Good chance for controlling abrupt climatic changes, as from volcanic eruption	Intensify rapidly; 5 year lag to decrease intensity	Yes by changing substances used	Possible by varying application by latitude	Not required once remedy agreed on	Probably low risk but needs careful research, particularly on impact on stratospheric chemistry. Ocean acidification not addressed	Could reduce adverse effects of solar radiation on earth. Possible liability problem. No ocean acidification mitigation.
H. Optimized radiative forcing by building flexible deflector in space between Earth and Sun as specified in endnote 23	High but no experience with building and maintaining anything so large so far from Earth	Appears to be high for warming. Other benefits, e.g., UV protection, plant growth, offset volcanic eruption	High for both heating and cooling unless cost is very high	0.2-2[f] (costs much less certain here, and probably underestimated—see text)	Probably fairer;[e] implementation costs borne by initiators; benefits and other possible costs received/ borne by all	Extremely high for both warming and cooling. Best chance for controlling abrupt climatic changes as from volcanic eruption	Intensify almost immediately by adjusting deflector	Yes by changing deflector placement	Not clear from available info; research required	Not required once remedy agreed on	Probably even lower risk than G but still needs careful research; quickly reversible if unforeseen problems. Ocean acidification not addressed.	Possible liability problem; no ocean acidification mitigation.

Prepared by Alan Carlin based on alternatives analyzed by Lasky, 2003 (remedy B), Keith 2000 (remedies C, D, E, and F), IPCC 2005 (E), NAS 1992 (F), Keith 2001 (G and H), Michaelson 1998 (columns 1, 4, & 6), and Teller et al. 1997, 1999, and 2002, and Wood's presentation in Tyndall 2004 (F, G, and H).

Footnotes for Table 2:

[a] Marginal cost in US dollars per ton carbon of CO_2 emissions (or equivalent) mitigated for row B only. Other costs in this column represent the range of estimated costs for categories of technology. There will be some cases where the costs of row B remedies are a lot less than the marginal cost.

[b] Does not apply; since none are mitigated, there is no cost of mitigation.

[c] Lasky (2003); see text for further discussion.

[d] Keith (2000).

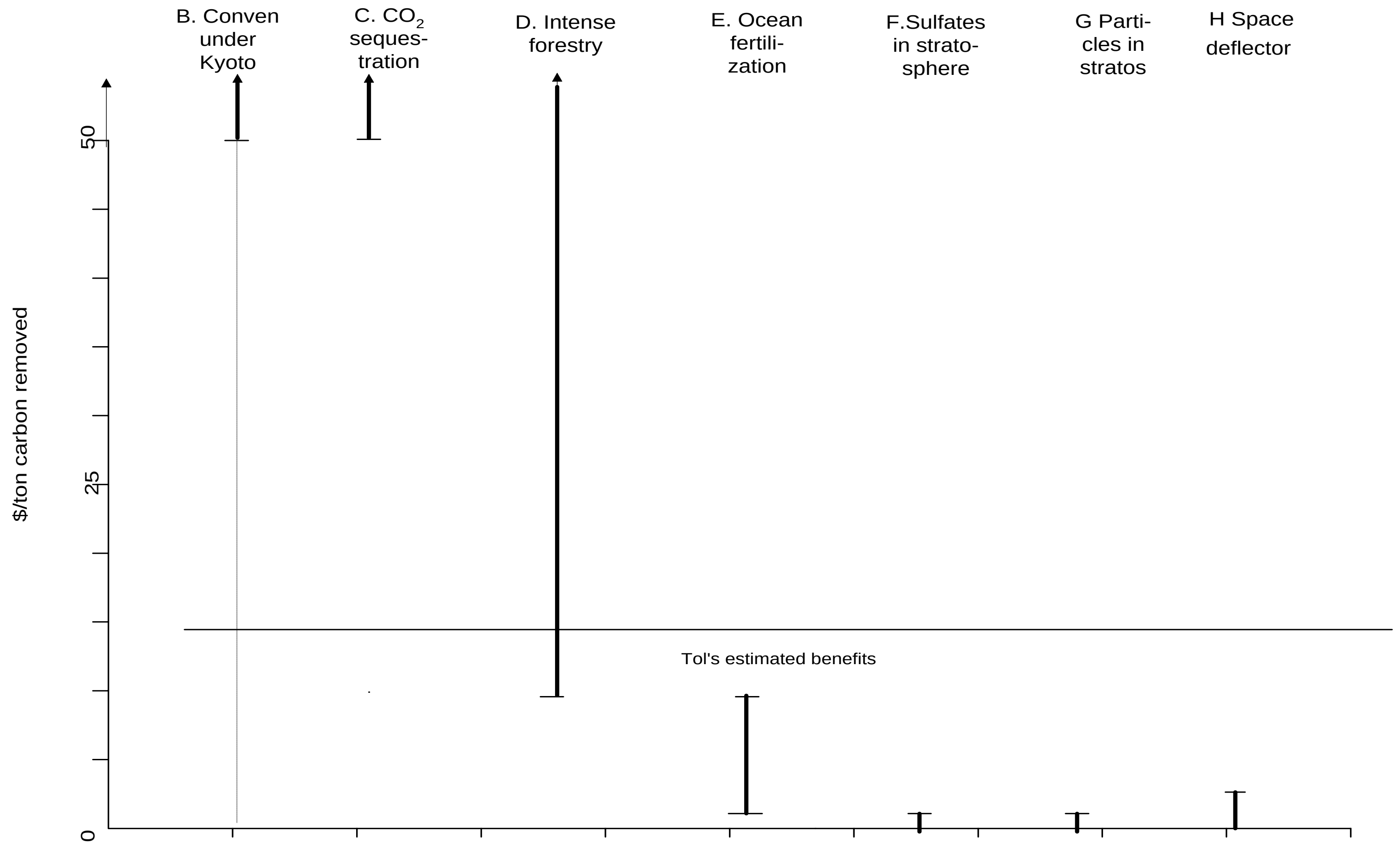
[e] Michaelson (1998)

[f] Keith (2001).

[g] This range of estimates assumes an estimated cost of $0.2-1.0 billion per year (from Wood, 2005) and an assumed offset of approximately 10 gigatons of carbon per year. Ten gigatons is representative of the carbon emission reduction needed to achieve a 450 ppmv CO_2 level in the atmosphere compared to projected IS92a emissions in 2060.

[h] IPCC (2005); based on Table SPM.5 with dollar values for capture from new large scale power plants with dollars per ton CO_2 converted to dollars per ton carbon.

Figure 1: Costs and Benefits of Carbon Removal



Prepared by Alan Carlin based on Table 2 for costs and Tol (2003) for benefits. Marginal cost in US dollars per ton carbon of CO_2 emissions (or equivalent) mitigated for column B only. Other costs represent the range of estimated costs for categories of technology. There will be some cases where the costs of row B remedies are less than the marginal cost and even less than benefits.

Endnotes for Main Text

[1] William J. Broad, “How to Cool a Planet (Maybe),” *New York Times*, June 27, 2006; also Crutzen (2006).

[2] See Breiterman for a recent survey of this literature. A very recent study suggests that there is a correlation between solar sunspot activity and global temperatures prior to 1970, and that the sun may be going into a quiescent period in which global temperatures could fall by 0.2oC. See Stuart Clark, “Global Warming: Will the Sun Come to Our Rescue?” *New Scientist.com*, September 16, 2006. Available at http://www.newscientist.com/article.ns?id=mg19125691.100&print=true

[3] “Eight Glacial Cycles from an Antarctic Ice Core,” *Nature*, Volume 429, June 10, 2004, pp. 623-8.

[4] “Climate Warning as Siberia Melts,” *New Scientist*, August 11, 2005, p. 12; Stafford (2006), Walter et al (2006).

[5] “Ice Sheet Instability,” *Science*, Vol. 311, March 24, 2006, pp.1698-1701.

[6] Walker, Gabrielle, 2006, “The Tipping Point of the Iceberg,” *Nature*, Vol. 441, No. 15, June.

[7] Tim Stephens, “New Findings Show a Slow Recovery from Extreme Global Warming Episode 55 Million Years Ago,” *UC Santa Cruz Currents Online*, Vol. 9, No. 41, June 13, 2005; available at http://currents.ucsc.edu/04-05/06-13/ocean.asp

[8] “Confronting the Bogeyman of the Climate System,” *Science*, Vol. 301, October 31, 2005, pp. 432-3.

[9] Defined as one that has a Volcanic Explosivity Index (VEI) of 8.

[10] H.R. 5642 (introduced in June 20, 2006) and S. 3698 (introduced July 20, 2006).

[11] BBC News, “Europe ‘Behind on Kyoto Pledges,’” http://news.bbc.co.uk/2/hi/uk_news/politics/4561576.stm, December 26, 2005.

[12] *Ibid.*

[13] Norm Dixon, “Global Warming: Can Kyoto Really Help?” *Baltimore Chronicle and Sentinel*, February 18, 2005.

[14] Figure 6, available at http://www.eia.doe.gov/oiaf/ieo/highlights.html

[15] Sources for “Extra Annual Emissions of CO2” figure: UDI-Platt’s, U.S. Energy Information Administration, and industry estimates; prepared by Scott Wallace, Staff Member, *Christian Science Monitor*, December 23, 2004.

[16] The International Energy Agency’s World Energy Outlook (WEO) Reference Scenario projects that, based on policies in place, by 2030 CO2 emissions will have increased by 63 percent from today’s levels, which is almost 90 percent higher than 1990 levels. Even in the WEO 2004’s World Alternative Policy Scenario—which analyzes the impact of additional mitigation policies up to 2030—global CO2 emissions would increase 40 percent on today’s level, putting them 62 percent higher than in 1990. See http://www.iea.org/textbase/npsum/ccsSUM.pdf

[17] Report on a presentation by Malte Meinshausen at a climate conference in Exeter, England, as reported in the *New Scientist*, February 3, 2005, http://www.newscientist.com/channel/earth/climate-change/dn6964

[18] One of the most prominent “prescriptions” (Pacala and Socolow, 2004) as to how emissions can be drastically cut includes an example of (2) since it proposes that annual average miles driven per vehicle be reduced from 10,000 miles to 5,000 miles based on “urban design, mass transit, and telecommuting.” To the extent that this is done through coercion rather than voluntary change (almost certain given people’s widely observed reluctance to give up using their cars), this would be an example of (2). An even more drastic proposal for actual individual emission rationing is reported under consideration in Great Britain. See David Adam, “Swipe-card plan to ration consumers’ carbon use,” *Guardian Unlimited*, July 19, 2006, http://www.guardian.co.uk/climatechange/story/0,,1823853,00.html

[19] Andrew C. Revkin, “Yelling ‘Fire’ on a Hot Planet,” *New York Times*, April 23, 2006.

[20] See Section 5.1 for a discussion of the economic costs. Some of the proponents of the Kyoto Protocol approach have recently made (Edenhofer et al, eds., 2006) quite sophisticated arguments concerning the effects of endogenous technical change on the costs of control, which they believe will bring down the cost of meeting the UNFCCC goal considerably. Although there would undoubtedly be endogenous technical change under their scenarios, these arguments are questionable on a number of grounds. They assume that much of the relevant technical change will result from “learning by doing” rather than from unrelated developments in other sectors. Experience with the development of motor vehicle hybrids, however, which depend on sophisticated computer technology, among other developments, make such assumptions dubious. They also appear to assume that increased R&D on emissions reduction technology will not have serious adverse effects on other sectors from which scarce R&D resources would be diverted since these costs appear not to have been factored in.

[21] For the most recent, see Wood’s presentation in Tyndall (2004):
More specifically, for global warming prevention:

---

* Controlled scattering of incoming sunlight back into space, by sub-microscopic *minimum-feature-size…*
  – Dielectrics – e.g., 100±20 nm spherules: σ~V2 << λ6
  – Metals – e.g., "optical chaff;"super-P metal balloon-ettes
  – Resonant scatterers – e.g., coated dye molecular clusters; fluorescence options: strato-heating; brighter photosynthetic bands
* 'Engineered scatterers' put into the stratosphere.
For global cooling prevention:
* "Long wave infrared chaff": 10 μm mesh Al screen & 0.1 μm 'ribs'
* Semiconductor (e.g., Si)-walled super-P balloon-ettes--pass optical insolation; reflect Earth-sourced long wave infrared.

[22] Technically, the deflector would be ideally placed at the L-1 Lagrange point between the Earth and the Sun and could be moved as needed from slightly off (to prevent ice ages) to directly on (to prevent global warming) the Earth-Sun line. The L-1 (Lagrange 1) point is a point in space on a direct line between the Earth and the sun, 1.5 million kilometres away. At that point, the gravity of the Earth is balanced with that of the Sun in such a way that anything placed there will, if gently nudged back into place every 25 days or so, orbit the Sun once every year. This means that it will remain directly between Earth and Sun with almost no fuel expenditure. Currently there is a solar observatory satellite called SOHO there. The more technical specifications of this option as proposed by Wood in Tyndall (2004) are:
- Total mass of 3,000 tons emplaced over 100 yrs.
  – 1 Shuttle-launch per year of construction mass
  – Area of 10^4km^2
- 'Raw' –cf. 10 MT previous design; ~0.01 MT 'dressed'
- ~30 μm-pitch (e.g., Al) metal screen –with ~25 nm 'ribs.'

[23] See Allenby (2003) for an expression of this. One example is to be found in the 2001 IPCC report, which has a very brief and general discussion of geoengineering approaches. It states that "although there may be possibilities" for it, "human understanding of the system is still rudimentary. The prospects of unanticipated consequences are large, and it may not even be possible to engineer the regional distribution of temperature, precipitation, etc. Geo-engineering raises scientific and technical questions as well as many ethical, legal, and equity issues. And yet, some basic inquiry does seem appropriate."

[24] Based on the chart on page 81.

[25] Although a dotted vertical line has been added to remedy B in Figure 1 to show the full range of costs.

[26] See also Casper Henderson, "Paradise Lost," *New Scientist*, Vol. 191, No. 2563, August 5, 2006, pp. 28-33, for a recent summary of the effects of acidification on the oceans.

[27] Based on an Email to the author from Lowell Wood of Stanford University and Lawrence Livermore National Laboratory. See also Schneider (2001) for similar views.

[28] Anne McIlroy, "Going to Extremes to Fight Global Warming," *Toronto Globe and Mail,* June 3, 2006; available at http://www.workopolis.com/servlet/Content/fasttrack/20060603/WARMING03?section=Science

[29] Ruddiman (2005a) has a description of what the world might look like under these circumstances.

[30] Nick Bunkley, "California Sues 6 Automakers over Global Warming," *New York Times*, September 21, 2006, p. C2.

[31] One recent suggestion along these lines has been made by Jagdish Bhagwati, "A Global Warming Fund Could Succeed Where Kyoto Failed," *Financial Times*, August 16, 2006. Available at http://www.ft.com/cms/s/7849f5b2-2cc3-11db-9845-0000779e2340.html/

[32] A related "Brazilian" proposal was actually considered in the negotiations leading to the Kyoto Protocol and has received some attention since. For a discussion see Chapter 7 of Baumert, 2002.

[33] Henry Fountain, "Climate Change: The View from the Patio," *New York Times*, June 4, 2006.

[34] For a much more comprehensive discussion of first three of these and other likely objections, see Michaelson (1998).