WHY A DIFFERENT APPROACH IS REQUIRED IF GLOBAL CLIMATE CHANGE IS TO BE CONTROLLED EFFICIENTLY OR EVEN AT ALL

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Proponents of greenhouse gas ("GHG") emissions reductions have long assumed that such reductions alone are the only, or at least the best, approach to global climate change control. This Article argues that there are a number of major uncertainties that any approach to climate change control needs to take into account, but that some very important conclusions can nevertheless be reached about the usefulness of reducing GHG emissions for the purpose of controlling climate change in spite of these uncertainties and without ignoring them. This Article first outlines an extensive list of problems involved in attempting to use emissions reductions to solve climate change problems. Then it explores the need for new, more understandable, and effective goals for climate change control. Finally, it outlines an alternative approach to climate change control that appears to solve many of the problems of attempting to use emissions reductions, including the many critical uncertainties, while more effectively and efficiently achieving two of the goals of such reductions.

This Article finds that the emissions reduction approach would be ineffective at solving the dangerous climate change effects of global warming because it would be technically risky, inflexible, extremely expensive, and politically unrealistic, a"nd would probably delay more effective and vastly less expensive measures using solar radiation management. This suggests the awful possibility that very large amounts of money may be spent in a fruitless attempt to reduce GHG emissions at the same time that all the possible adverse economic consequences of climate change are realized.

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In attempting to control climate change, the world is faced with potentially catastrophic losses but also with very large uncertainties. Wisdom would be to build a flexible control system that can handle all significant risks inexpensively and with a high probability of success. Solar radiation management either alone or with GHG emissions reductions justifiable on other grounds, offers the best and probably only realistic alternative for controlling global temperatures and avoiding dangerous climate changes. Solar radiation management requires some development to optimize operational details, comparatively modest funding, a reliable command and control system, and a legal change—all of which has not started. Both GHG emissions reductions and solar radiation management need to be implemented with great caution given the risk of unintended consequences in both approaches. This is unlikely to happen if action is delayed until a future possible emergency occurs as a result of possible climate change. Controlling sea level rise would appear to be a more useful objective than GHG emissions control or carbon dioxide levels but needs research. Solar radiation management would not solve the potential ocean acidification problem, which needs additional research and probably future action once the problem and solutions to it are better understood.

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INTRODUCTION

A. Definitions

It is important to start by defining two unusual terms that I have created for this Article or are not widely understood. The first is exclusive regulatory de-carbonization ("ERD"). ERD is defined as a strategy for decreasing emissions of greenhouse gases ("GHGs") as the exclusive approach used to control global warming. Most current climate change control proposals involve some form of ERD such as regulations, emission taxes, fuel economy, bio-fuel standards, and "cap and trade" proposals. ERD assumes that if we could just reduce carbon emissions that humans are putting into the environment, the global warming ("GW") problem would be solved. I have termed such attempts ERD because most, but not all, involve decreasing various forms of carbon emissions. If accomplished, such decreases would reduce the levels of GHGs that would otherwise accumulate in the atmosphere.[1] ERD is intended to include governmental actions that are coordinated between nations (such as under the Kyoto Protocol) or done independently by each country, state or other political jurisdiction.

The second term is solar radiation management ("SRM"). SRM is human-directed management of the amount and characteristics of incoming solar radiation to part or all of the Earth. It is one type of atmospheric geoengineering.

B. Principal Effects of Climate Change

Fundamental to a rational decision as to what to do about global climate change is what the problems are that need to be solved, what and how much needs to be done, and how soon to solve the problems. It is sometimes forgotten that the objective of global climate change control should not be to reduce emissions of GHGs, but rather to reduce specified risks resulting from climate change. Previous research has shown that the very widely proposed approach of reducing emissions of GHGs is not likely to be either effective or efficient in reducing the risk of dangerous climate changes or accomplishing some of the other goals of climate change

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[1] This would lower the top line representing GHG emissions in Figure l(a). Figure l(a) shows the levels of various climate forcings over time since 1880. *Infra* Figure l(a).

control.[2] The three principal direct effects would appear to be the following based on current knowledge:[3]

(E1) Increasing risk of abrupt, non-linear climate changes/tipping points. These are dangerous, self-reinforcing climate changes, and would appear to be the most critical risk since they could cause a regional or global disaster.[4]

(E2) Gradual increases (or possibly even decreases) in global temperatures and their effects on humans and ecosystems is the best known risk. Some people (those living in cold climates) might welcome gradually increasing temperatures. Others (those living in very warm climates) probably would not. Almost everyone would face some adaptation expenses.

(E3) Non-temperature effects of climate change such as increasing atmospheric GHG levels, especially the effects of increasing carbon dioxide (CO_2) levels on the oceans. The resulting acidification is believed to already be affecting shellfish and coral reefs. This may be the most difficult problem to solve.[5]

Although most public discussion has addressed E2, the technical discussion has rightly centered on El as the basis for setting de-carbonization goals, since the feared environmental changes could well be catastrophic and possibly irreversible.

C. Underlying Theme—Climate Change Science is at Best Uncertain

Perhaps because of the seeming unanimity of the reports from the Intergovernmental Panel on Climate Change ("IPCC"), one of the most important, but often overlooked, aspects of climate change is the very large scientific uncertainties involved. Uncertainties create risks. And these risks can be catastrophic in nature if they substantially endanger the welfare of a large enough number of people or ecosystems. In deciding how to respond to the problems posed by climate change, it is very important to select an approach that will take into account these risks and

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[2] Alan Carlin, *Global Climate Change Control: Is There a Better Strategy than Reducing Greenhouse Gas Emissions?*, 155 U. PA. L. REV. 1401 (2007), *available at* http://pennumbra.com/issues/pdfs/155-6/Carlin.pdf [hereinafter Carlin, *Global Climate Change Control]*.

[8] *Id.* at 1409-10. In my previous article I posited four direct effects of global warming.

[4] See *infra* Section I.A.3 for a discussion, examples, and references to these potential dangerous climate changes; see *also id.* at 1420-24.

[6] See *infra* Section II.B.3; see *also* Carlin, *Global Climate Change Control, supra* note 2, at 1472-76.

provide an effective means to avoid them if they appear credible, significant, or threatening.

The major reason for these uncertainties is the sheer complexity of the Earth's climate system and the difficulty of determining what the effect of changes to it might be. The following states the problem very well:

> For more than 100 years, climate scientists have fully understood that if all else were held constant, an increase in the atmospheric concentration of carbon dioxide (CO_2) would lead to an increase in the near-surface air temperatures. The problem becomes a lot more complicated in the real world when we consider that "all else" cannot be held constant and there are a lot more changes occurring at any one time than just the concentration of CO_2. Once the temperature of the Earth starts inching upward, changes immediately occur to atmospheric moisture levels, cloud patterns, surface properties, and on and on. Some of these changes, like the additional moisture, amplify the warming and represent positive feedback mechanisms. Other consequences, like the development of more low clouds, would act to retard or even reverse the warming and represent negative feedbacks. Getting all the feedbacks correct is critical to predicting future conditions, and these feedbacks are simulated numerically in global climate general circulation models (GCMs). Herein lies a central component of the great debate—some GCMs predict relatively little warming for a doubling of CO_2, and others predict substantial warming for the same change in atmospheric composition.
>
> If that is not enough, changes in CO_2 in the real world would almost certainly be associated with other changes in the atmosphere—sulfur dioxide, mineral aerosols (dust), ozone, black carbon, and who knows what else would vary through time and complicate the "all else held constant" picture. By the way, the Sun varies its output as well. And when discussing climate change over the next century, even more uncertainties come from estimations of economic growth, adoption of various energy alternatives, human population growth, land use changes, and . . . you get the message.[6]

[6] World Climate Report, Global Warming: Not So Fast (Feb. 21, 2008), http://www.worldclimatereport.com/index.php/2008/02/21/global-warming-not-so-fast/.

Some important uncertainties are also created by the fact that the Earth is not believed to have experienced the temperatures now predicted for this century in approximately thirty-five million years; therefore, humans have no real experience with what all the effects of such temperature increases might be.[7] Recent research on sea level rise during the previous interglacial period, approximately 120,000 years ago, found that sea levels rose as rapidly as 1.6 meters per century and reached a level about four to six meters higher than present. At this time global temperatures were about 2°C above current levels under what is believed to be much weaker climate forcing than at present.[8] Whether this would be the case under current circumstances is uncertain, but it is plausible that the climate forcing could be higher now. Beyond a 2°C increase, however, there is little guidance as to what might happen. One possible scenario, for example, is that such temperatures, magnified as they are expected to be in polar areas, would lead to the melting of much of the permafrost in the Arctic.[9] There is concern that this could lead to the release of twice as much GHGs as humans have released so far;[10] which, in turn, could lead to a runaway greenhouse effect and still higher temperatures.

Another major source of uncertainty is created by questions concerning the relative significance of GHG levels in explaining climate changes and the possibility of variations in basic physical measurements (such as temperatures) outside of those experienced in recent decades and inconsistent with the current GHG hypothesis of global warming. Although the IPCC claims near unanimity for its conclusions,[11] there remain a significant number of skeptics who do not agree.[12] Even one prominent

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[7] *See Eminent Scientists Warn of Disastrous Permanent Global Warming*, ENV'T NEWS SERVICE (Feb. 19, 2007) (noting that current temperatures "rival those of the Eocene epoch"); Daniel P. Schrag, Confronting the Climate-Energy Challenge, Presentation spon sored by the American Meteorological Association (Jan. 18, 2007) [hereinafter Schrag Presentation], *available at* http://www.ametsoc.org/atmospolicy/documents/Schrag_AMS 12182007.pdf (noting that the Eocene epoch was the last time Earth's atmospheric carbon dioxide was above 500 ppm).

[8] E.J. Rohling et al., *High Rates of Sea-Level Rise During the Last Interglacial Period*, 1 NATURE GEOSCI. 38,38 (2008), *available at* http://www.nature.com/ngeo/journal/vl/nl/ fuiyngeo.2007.28.html.

[9] Sergey A. Zimov et al., *Permafrost and the Global Climate Budget*, 312 SCIENCE 1612, 1612 (2006).

[10] Schrag Presentation, *supra* note 7.

[11] *See* Intergovernmental Panel on Climate Change, IPCC Reports, http://www.ipcc.ch/ ipccreports/index.htm (last visited Apr. 4, 2008).

[12] *See, e.g.*, News Release, Heartland Institute, New York Global Warming Conference Considers 'Manhattan Declaration' (Mar. 4,2008), *available at* http://www.heartland.org/ Article.cfm?artld=22866.

non-skeptic appears to agree.[13] The climate system is extremely complicated and the GHG hypothesis together with other recognized influences ("climate forcings") on climate do not fully explain all of the available historical climate observations even for the current Holocene Epoch.[14] The IPCC is basically using computer models to predict future climate and temperatures. These models are only as good as the relationships they assume and the data that they use.

The most prominent alternative to the GHG explanation for GW during the Holocene primarily attributes much more significance to solar variability.[15] Advocates argue that changes in the sun's eruptional activity, solar wind, and magnetic field, among other characteristics, have been major determinants of global temperature here on Earth.[16] Since this has not been taken into account in the IPCC models to date, these models may need to be changed if they are to more accurately reflect reality.[17]

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[13] Stephen Schneider, Edge: Modeling the Future - A Talk with Stephen Schneider (Apr. 1, 2007), *available at* http://www.edge.org/3rd_culture/schneider08/schneider08_index.html ("Warming is unequivocal, that's true. But that's not a sophisticated question. A much more sophisticated question is how much of the climate Ma Earth, a perverse lady, gives us is from her, and how much is caused by us. That's a much more sophisticated, and much more difficult question.").

[14] HENRIK SVENSMARK & NIGEL CALDER, THE CHILLING STARS : A NEW THEORY OF CLIMATE CHANGE (2007).

[15] *Id*. For a general history of research in this area, see Spencer Weart, Changing Sun, Changing Climate? The Discovery of Global Warming (Aug. 2007), http://www.aip.org/history/climate/solar .htm. For recent particularly relevant research, see Nicole Scafetta & Bruce Wood, *Is Climate Sensitive to Solar Variability?*, PHYSICS TODAY, Mar. 2008, at 50-51; *see also* Theodore Landscheidt, New Little Ice Age Instead of Warming 14 ENERGY & ENV'T 327 (2003); Richard Mackey, *Rhodes Fairbridge and the Idea that the Solar System Regulates the Earth's Climate*, 50 J. OF COASTAL RES. 955 (2007); I. Charatoya, *Can Origin of the 2400-Year Cycle of Solar Activity Be Caused by Solar Inertial Motion?*, 18 ANNALES GEOPHYSICAE 399-405 (2000). For a summary of recent developments in the Svensmark discussion, see Jacopo Pasotti, *Geophysics: Daggers Are Drawn Over Revived Cosmic Ray-Climate Link*, 319 SCIENCE 144 (2008); *see also* Vincent Courtillot et al., *Are There Connections Between the Earth's Magnetic Field and Climate*, 253 EARTH & PLANETARY SCI. LETTERS 329-39 (2007). These findings are at considerable variance with the IPCC discussion of the contribution of solar variability to climate. See P. Forster et al., *Changes in Atmospheric Constituents and in Radiative Forcing, in* CLIMATE CHANGE 2007: THE PHYSICAL SCIENCE BASIS: CONTRIBUTION OF WORKING GROUP I TO THE FOURTH ASSESSMENT REPORT OF THE INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE 188-93 (S. Solomon et al. eds., 2007).

[16] Forster et al., *supra* note 15, at 188-93; see *also* Henrik Svensmark et al., *Experimental Evidence for the Role of Ions in Particle Nucleation under Atmospheric Conditions*, 463 PROC. ROYAL SOC''Y 385 (2007).

[17] This assumes that solar variability should prove to have a significant influence on climate.

Unfortunately, despite every effort to consciously avoid doing so, it is all too easy to develop models that explain historical data by "fitting the data"; it is much harder to accurately predict future events using such models. So the ultimate test of the significance of GHGs in climate change may not come as a result of new scientific inquiries using current knowledge, but rather from experience over coming years and comparisons of this experience with the predictions that have been made. If global temperatures should decline further despite continuing increases in GHG levels, as some skeptics and experts have predicted, advocates of the GHG explanation for GW may have a difficult time explaining the new data in terms of their hypothesis.[18] If, on the other hand, temperatures start increasing rapidly at the same time that solar activity decreases, the skeptics may have a difficult time explaining how that could be. In 2007 the IPCC concluded that they were at least ninety percent certain that human emissions of GHGs rather than natural climate variations were warming the planet.[19] That leaves up to a ten percent risk, according to the IPCC, that this conclusion might be erroneous. Some observers have pointed out that the solar magnetic field has been unusually low since a sudden drop in late 2005 and that the next solar cycle, sunspot cycle 24, appears to be late starting and that this may presage a colder period for global temperatures.[20] If the increase in temperatures is not largely due to higher GHG

[18] Three of the four principal indices of global temperatures recorded their highest tem peratures in recent years in 1998, so can be said to have been declining since then. Anthony Watts, 4 Sources Say "Globally Cooler" in the Past 12 Months, Watts Up with That? (Feb. 19,2008), http://wattsupwiththat.wordpress.com/2008/02/19/january-2008-4-sources-say-globally-cooler-in-the-past-12-months [hereinafter Watts, 4 Sources Say]. Recently there actually have been some early indications that something like this might be happening. As usual, it is very hard to distinguish random climate events from a new trend. But all four of the indices show surprisingly large drops between January 2007 and January 2008, which may or may note be a precursor of further declines. This 2007-2008 decline brings global temperatures back to about what they were in 1930, depending on which index is used. *Id.*

[19] INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE, CLIMATE CHANGE 2007: THE PHYSICAL SCIENCE BASIS, SUMMARY FOR POLICY MAKERS 8 (2007), *available at* http://www.ipcc.ch/pdfassessment-report/dr4/wgl-spm.pdf. "Most of the observed increase in globally averaged temperatures since the mid- [twentieth] century is *very likely* due to the observed increase in anthropogenic greenhouse gas concentrations." *Id.* at 3 n.6 (defining "very likely" as a greater than ninety percent probability of occurrence).

[20] Anthony Watts, Where Have All the Sunspots Gone?, Watts Up with That? (Feb. 13, 2008), http://wattsupwiththat.wordpress.com/2008/02/13/where-have-all-the-sunspots-gone. It is interesting, but hardly conclusive, to compare the four temperature charts refer enced in Watts, 4 Sources Say, *supra* note 18, with the observed geomagnetic averaged planetary index referenced in this footnote, particularly the sharp drop in late 2005.

levels, as currently hypothesized by the IPCC, reducing GHG emissions may have less effect than the advocates of GHG emission controls now believe.[21] All this is not to argue that the GHG explanation of current global warming is wrong—only that the climate system may be more complicated than our current understanding of it and that there exists more uncertainty than is often acknowledged. The important thing is to take these uncertainties into account in proposing an effective and efficient control approach rather than ignoring them and making guesses as to what assumptions to make as to climate sensitivity to increased GHG levels or adopting a single hypothesis that discounts the substantial evidence of the impact of solar variability on Earth's climate.

A third major source of uncertainty is created by the very large adverse effects that may result if abrupt non-linear climate changes (El) should occur. Since the magnitude, timing, and probability of these effects are themselves very uncertain, this is still another important uncertainty that needs to be taken into account when control measures and the analysis of them are considered.[22]

Anthony Watts, A Look at Temperature Anomalies for All 4 Global Metrics: Section I, Watts Up With That? (Feb. 27,2008), http://wattsupwiththat.wordpress.com/2008/02/27/a-loo-at-temperature-anomalies-for-all-4-global-matrics. The question of the relative influence of solar versus GHG changes is further compounded by research published in 2007 which concludes that:

> There is considerable evidence for solar influence on the Earth's pre-industrial climate and the Sun may well have been a factor in post-industrial climate change in the first half of the last century. Here we show that over the past 20 years, all the trends in the Sun that could have had an influence on the Earth's climate have been in the opposite direction[1] to that required to explain the observed rise in global mean temperatures.

Mike Lockwood & Claus Frohlich, *Recent Oppositely Directed Trends in Solar Climate Forcings and the Global Mean Surface Air Temperature*, 463 PROC. ROYAL SOC'Y 2447, 2447 (2007). For a contrary view, see HENRIK SVENSMARK & EiGlL FRIIS-CHRISTENSEN, DANISH NAT'L SPACE CTR., REPLY TO LOCKWOOD AND FROHLICH—THE PERSISTENT ROLE OF THE SUN IN CLIMATE FORCING (2007), *available at* http://www.spacecenter.dk/publications/scientific-report-series/Scient_No._3.pdf.

[21] Scafetta & Wood, *supra* note 15, at 50 (concluding that the Sun "could account for as much as 69% of the increase in Earth's average temperature," contrary to the conclusions of the IPCC, and "[furthermore, if the Sun does cool off, as some solar physicists predict will happen over the next few decades, that cooling could stabilize Earth's climate and avoid catastrophic consequences predicted in the IPCC report").

[22] Martin L. Weitzman, *On Modeling and Interpreting the Economics of Catastrophic Climate Change*, REV. ECON. & STAT. (forthcoming 2008) (manuscript 1-2), *available at* http://www.economics.harvard.edu/faculty/weitzman/files/modeling.pdf.

One of the more unfortunate aspects of the large uncertainties involved in trying to predict future climate is that there has been a tendency for the IPCC to underestimate the actual temperature increases and related effects in the Arctic that have recently been observed.[23] This is presumably not because they wanted to, but may rather be because the process of gaining a consensus and the use of models based on previous experience naturally reduces the estimates of extreme values which may be proposed, particularly at temperatures outside the realm of previous measurements. The requirement for consensus presumably in this case favored the use of more "conservative" (i.e., nearer recent experience), more easily documented assumptions. These risks appear to be credible possibilities; what is unknown is how important they will turn out to be as humans continue with the experiment of putting large quantities of GHGs into the atmosphere.

Given these major uncertainties, it would be very easy to conclude that very little could reasonably be said about how best to control global warming. This Article, however, argues that some very important conclusions can nevertheless be reached about the usefulness of reducing GHG emissions for the purpose of controlling climate change in spite of these uncertainties and without assuming them away. It will do so by first outlining the major problems involved in attempting to use the widely proposed ERD to solve climate change problems (Section I). Then it will outline the need for new, more understandable, and effective goals for climate change control (Section II). Next it will discuss an alternative approach to climate change control that appears to solve many of the problems of attempting to use ERD (Section III) while more effectively and efficiently achieving the goals of ERD. Finally, it will offer some conclusions.

I. ERD WOULD BE UNLIKELY TO ACHIEVE CLIMATE CHANGE CONTROL GOALS

There are numerous problems with pursuing ERD as the approach to control global climate change. This section will explain why such an approach would be technically risky, inflexible, extremely expensive, and politically unrealistic.

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[23] Stefan Rahmstorf et al., *Recent Climate Observations Compared to Projections,* 316 SCIENCE 709,709 (2007); *see* Daniel P. Schrag, *Confronting the Climate-Energy Challenge,* 3 ELEMENTS 171,174 (2007) [hereinafter Schrag, *Confronting]* (stating that the Keeling curve underestimates human impact on climate).

A. Technically Risky

From a technical perspective ERD would have great difficulty in achieving any specific climate change control goals expressed in terms of the major effects. There are a number of reasons for this, which will be discussed in this section. The first is our inability to accurately determine climate sensitivity[24] and other effects of GHGs in advance. The second is ERD's inability to avoid rapid polar and particularly Arctic warming and, therefore, sea level rise should it continue. The third is that ERD is unlikely to be able to prevent potential abrupt climate changes (Els). The fourth is that ERD itself can have major adverse environmental effects. Finally, the important uncertainties in predicting future climate changes suggest that we may not know enough to justify large investments in ERD for climate change control purposes, at least until they are much better understood.

1. Inability to Accurately Determine Climate Sensitivity and Hence Emissions Reductions Needed

It appears unlikely that the climate system will ever be understood sufficiently well to determine the extent to which GHG emissions must be controlled decades in advance using ERD or the benefits of doing so. Climate sensitivity, the key technical variable describing climate temperature sensitivity to increased GHG levels, appears to be unknowable in advance.

In order to determine the extent of the emissions reductions which ERD advocates propose, it is necessary to make a large number of assumptions as to important physical relationships for which we do not have and, in some cases, may never have proven relationships. One of the most important of these parameters is the relationship between a doubling of CO_2 levels and global temperatures, the so-called climate sensitivity factor.[25] But there are many others as well, ranging from the validity of current atmospheric and glacial flow models to fundamental factors influencing climate that we may not yet fully understand. Because the Earth's climate system is very complex and scientific understanding of it is far from complete, new information and significant refinements of existing knowledge

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[24] For a definition of climate sensitivity, see Roe & Baker, *infra* note 27 and accompanying text.
[25] Schrag, *Confronting*, *supra* note 23, at 172-74.

have occurred in recent years, should be expected in the future, and are likely to prove to be the rule rather than the exception. And as discussed in introductory Section C above, current projections indicate that the Earth is likely to experience higher temperatures than previously experienced by humans with the result of humans having very little knowledge of what may happen as a result. The United Nations Framework Convention on Climate Change ("UNFCCC") process has drawn on many eminent experts through the iterative IPCC process, perhaps to try to minimize this problem.[26] It is already evident, however, that this process so far has tended to fairly consistently underestimate the seriousness of the problem with regard to the Arctic compared to recent observations. Subsection 2 below documents a number of important polar areas where there appear to have been such underestimates. But more generally, another problem posed by the IPCC process is that such attempts to create scientific consensus on a subject are basically antithetical to the nature of science. Science advances through a process of creative destruction, not consensus building. Put another way, unless new ideas are allowed to be proposed and tested, science will not advance. And it would be hard to find an area which has a greater need to advance than climate science given the large uncertainties and its inherent chaotic nature.

The most fundamental uncertainty is the climate sensitivity factor, on which every estimate of required emissions reductions must be based. A recent study explains why this crucial factor may never be known with any accuracy in advance.[27] The study makes a number of points, including that little progress has been made in determining the climate sensitivity factor, that the conclusion results from the basic nature of climate, that there are fat "tails" of possible extreme outcomes, and that if extreme events are set in motion, the outcome is difficult to predict from today's data.[28] The study concludes that we must, therefore, concentrate on temperature (or possibly related) targets, not unknowable emissions targets.[29]

Obviously, if it is not possible to know climate sensitivity fairly accurately in advance, it is not possible to accurately determine the atmospheric GHG levels required to avoid breaching a specified global temperature

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[26] United Nations Framework Convention on Climate Change, http://unfcc.int/2860.php (last visited Apr. 4, 2008).
[27] Gerard S. Roe & Marcia B. Baker, *Why is Climate Sensitivity So Unpredictable?*, 318 SCIENCE 629,629 (2007).
[28] *Id.*
[29] *Id.* at 632.

level. And if no required atmospheric GHG level can be accurately determined, there is little basis for determining the required emissions reductions to achieve that level. An overestimation of the GHG emission reduction levels required would result in extremely expensive over-control which would achieve no real purpose.[30] An underestimation of emission reductions required would mean that the objectives would not be achieved, with whatever adverse effects in which this might result.

Without an accurate knowledge of the climate sensitivity factor in advance, ERD is based on nothing more than an informed guess. Do we really want to gamble the climate future of the world on informed guesses? I do not think so.

2. Inability to Avoid Threatened Rapid Arctic Warming and, Therefore, Sea Level Rise

In the last few years there have been a number of disturbing climate changes, particularly in the polar areas, that suggest that the polar warming problem may be more serious than the picture painted by the IPCC, and even by some proponents of emissions reductions. This section will summarize some of the most significant changes in order to illustrate that there are substantial uncertainties in our understanding of Earth's climate system and the inability of ERD to prevent such changes. This is not intended to say that such disturbing changes will continue in the future, since I argue that we do not know enough to say. It does illustrate, however, the difficulties of trying to guess far in advance what will happen to Earth's climate and therefore what may need to be done to control such changes.

Arctic temperatures have been increasing rapidly since the early 1990s while the mass of the Greenland Ice Sheet ("GIS") and the extent of Arctic Sea ice have been decreasing rapidly in the last few years.[31] 2007 represented a dramatic year in this regard in that both the GIS and Arctic

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[30] For what it may be worth, one recent comprehensive study based on Antarctic ice cores covering the last 42,000 years suggests that the climate sensitivity factor was between 1.3 to 2.3°C compared to the IPCC's range of 2.0 to 4.5°C. See Petr Chylek & Ulrike Lohmann, *Aerosol Radiative Forcing and Climate Sensitivity Deduced from the Last Glacial Maximum to Holocene Transition,* 35 GEOPHYSICAL RES. LETTERS L04804 (2008). If their estimates should hold going forward, this would mean that temperature changes due to increases in CO_2 levels would be much lower than the IPCC predicts.

[31] Rune G. Graversen et al., *Vertical Structuring of Recent Arctic Warming,* 451 NATURE 53, 53 (2008).

Sea ice have decreased by unexpectedly large amounts.[32] Like other scientific issues involving climate change, it is unclear how much of this is due to global warming and how much to other causes.[33] In any case, if this Arctic warming is a trend rather than a short-term climatic variation, ERD is not likely to be very useful in averting the serious effects that such temperature increases in the Arctic may have on humans and ecosystems. There is already speculation that a major "tipping point" has been reached.[34] There are at least two reasons to worry that this could be the case. The first is that the albedo of snow is much greater than that of water.[35] As sea ice melts, it is replaced by open water, which absorbs most of the sunlight hitting it. The result is a positive feedback in which the loss of sea ice leads to additional ocean warming from absorbed sunlight.[36] A second possible feedback effect concerns the potential release of methane from warming permafrost, which could potentially release more GHGs than man has so far managed to do.[37]

If Arctic warming continues at the current rapid rate, ERD is not likely to be very useful in responding to this warming, given the time required for a scientific consensus to be formed, suitable models built, international political agreement reached, and GHG reductions actually implemented. It appears unlikely that it would be possible to even determine what GHG reductions would be necessary to avoid undesirable Arctic warming. Its rapidity was also not predicted by the IPCC or existing models, which does not increase confidence in the idea that future use of ERD could reasonably be based on such a scientific consensus far enough in advance of the event to make it useful. If these changes are the result of current atmospheric GHG levels, preventing future Arctic warming using ERD could require the actual removal of GHGs already in the atmosphere rather than the comparatively far easier task of decreasing future GHG emissions into the atmosphere.

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[32] Mark Serezze, Arctic Sea Ice Melt, Presentation at a Seminar Sponsored by the American Meteorological Association (Nov. 26,2007) [hereinafter Serezze Presentation], *available at* http://www.ametsoc.org/atmospolicy/documents/ams_serreze_briefing.pdf.
[33] Graversen et al., *supra* note 31, at 55.
[34] There is considerable difference of opinion on this subject. *See, e.g.*, Keith Sherwood & Craig Idso, *Declining Arctic Sea Ice: Has a "Tipping Point" Been Passed?* 10 CO_2 SCI. (2007), http://www.co2science.org/articles/V10/N40/EDIT.jsp.
[35] *Polar Albedo—the Earth's White Caps Help Keep the Climate in Balance*, SCI. POLES, Jan. 31,2006, http://www.sciencepoles.org/index.php?/articles/polar_albedo_the_earths_white_caps_help_keep_the_climate_balance/&s=2&rs=home&uid=625&lg=en&category=3.
[36] *Id.*
[37] Fred Pearce, *Climate Warming as Siberia Melts*, NEW SCI. Aug. 11,2005, at 12, *available at* http://environment.newscientist.com/article/mgl8725124.500.html.

This section will discuss five such disturbing polar climate and related changes: (a) changes in Arctic Sea ice, (b) Greenland Ice Sheet mass losses, (c) collapse of polar ice shelves, (d) West Antarctic Ice Sheet losses, and (e) sea level rise.

a. Arctic Sea Ice Decreases

Arctic Sea ice reached the lowest extent ever recorded at the end of the Arctic summer in September 2007,[38] and was younger and thinner than in previous years.[39] Even worse, the ice extent appears to have dropped well below a long-term downward trend line going back as far as 1979 and appears to represent a sharp break with the latter part of the twentieth century.[40] Sea ice coverage was about thirty-eight percent below the long-term average for late summer, and twenty-three percent below the previous recorded low two years previously.[41] Arctic Sea temperatures were 3.5°C warmer than average and 1.5°C warmer than the previous recorded high.[42] This warmer water greatly reduced the thickness of sea ice in the summer of 2007—about five times the normal loss from this cause.[43] Furthermore, the sea ice extent appears to be significantly lower than that predicted by even the most pessimistic of the IPCC models.[44] Given that these decreases have accelerated in very recent years it is difficult to see how ERD could act rapidly enough to prevent further decreases of this magnitude and rapidity assuming that the current short-term trend continues. The current decreases may or may not be the result of increases in the current ambient levels of GHGs in the atmosphere. These levels would not be decreased by ERD; the only effect of decreases in GHG emissions might be to decrease the rate of increase in temperatures and decrease the possible future loss of Arctic Sea ice compared to what it might otherwise have been. If sea ice continues to decrease and if there is a desire not to have that happen, there is no easy way to determine what change in GHG emissions levels would be necessary. In fact, it appears

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[38] Serezze Presentation, *supra* note 32, at 2-3.
[39] *Id.* at 12.
[40] *Id.* at 3.
[41] Sid Perkins, *Portrait of a Meltdown: Many Factors Led to 2007's Record Low in Arctic Sea Ice*, 172 SCI. NEWS 387, 387 (2007).
[42] *Id.*
[43] *Id.* (quoting Donald Perovich of the U.S. Army Cold Regions Research and Engineering Laboratory in Hanover, NH).
[44] Serezze Presentation, *supra* note 32, at 7.

likely that it might require an end to all new GHG emissions and the actual removal of GHGs already in the atmosphere. Neither of these are either practically feasible or likely currently. As previously noted, a very disturbing result of the decreasing extent of Arctic Sea ice is that it greatly decreases the surface albedo, which results in increased absorption of the Sun's energy by the sea. Whether this is the reason for the much warmer water temperatures is not known. This would be a positive feedback from sea ice losses.

b. Greenland Ice Sheet Losing Mass

Temperatures in Greenland have increased rapidly since about 1990, although they were higher in the mid-20th century.[45] Between the 1960s and 1990s, changes in the Greenland Ice Sheet ("GIS") appear to have been due to regional rather than global changes.[46] The past fifteen years show a statistically significant link with global temperatures and increased ice melting.[47] Southern Greenland's climate is currently responsive to general Northern Hemisphere warming and may be highly susceptible to further such warming.[48]

The GIS has experienced increasing melt areas since 1979 with an upward trend line. In 2007 the area exceeded the previous maximum during this period by ten percent.[49] This also results in a positive adverse feedback since areas either with meltwater on the surface or that have previously had meltwater on them have much lower albedo.[50] Recent studies of GIS mass have concluded that there is a substantial loss which may be accelerating. Ice mass losses are about 238 cubic kilometers per year, or about 0.5 mm per year in terms of sea level rise.[51]

Head of NASA Goddard Space Flight Center's Cryosphere Sciences Branch Waleed Abdalati concludes that:

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[45] Edward Hanna et al., *Increased Runoff from Melt from the Greenland Ice Sheet: A Response to Global Warming*, 21 J. CLIMATE 331, 331-41 (2008).
[46] *Id*.at 338-39.
[47] *Id*.
[48] *Id*.at 332.
[49] Konrad Steffan, Greenland Ice Sheet: Dynamic Response to Global Warming, Presentation at seminar sponsored by the American Meteorological Society, Slide 9 (Nov. 26, 2007), *available at* http://www.ametsoc.org/atmospolicy/documents/Gr%20AMS%20congressional%20%20briefing.pdf.
[50] *Polar Albedo, supra* note 35.
[51] Steffan, *supra* note 49, at 13 (citing Isabella Velicogna & John Wahl, *Acceleration of Greenland Ice mass Loss in Spring 2004*, 443 NATURE 329 (2006)).

> While differences in these studies still exist,... collectively, they very convincingly paint a picture of the Greenland Ice Sheet as having been close to balance in the 1990s, contributing a small amount to sea level, but becoming significantly out of balance and losing a substantial amount of ice to the sea in the last several years.[52]

It appears to be a credible possibility that the accelerating erosion of the GIS may continue and that would contribute to a higher sea level; which would adversely affect human infrastructure and would be very difficult, if not impossible, to reverse. But if ERD were used to avoid this possibility, it is difficult to see how GHG emissions reductions can be related to future GIS losses if the objective were to stabilize the GIS, or that ERD would have any immediate effect on the current acceleration even if a reliable relationship could be established. The models used by the IPCC ignore the possible disintegration of ice shelves and resulting speedup of glaciers, so they are unable to predict any global sea level rise from this source due to warming.[53] It is possible that such models can be built, but in the meantime it would be difficult to determine what particular change in GHG emissions would be needed to stabilize the GIS or how soon that might occur using ERD. Hence if GIS stabilization were the objective, selection of an emissions reduction objective would, at best, be an informed guess.

c. Collapse of Polar Ice Shelves

In both the Arctic and the Antarctic Peninsula ice shelves which are believed to have existed for many thousands of years have been collapsing in recent years. The best known of these is the Larsen B Ice Shelf on the Antarctic Peninsula, which collapsed in 2002 over a thirty-five day period.[54] The collapse has been attributed to the buildup of melt water ponds in late January, apparently in response to an unusually warm summer and extended melt season.[55] Most of these ponds disappeared in

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[62] Kendall Haven, *Greenland's Ice Island Alarm,* NASA EARTH OBSERVATORY, Aug. 28, 2007, http://earthobservatory.nasa.gov/Study/Greenland/greenland5.html.
[53] Anil Ananthaswamy, *Peering Beneath Glacier Might Explain Speedier Slide,* NEW SCI., Feb. 4, 2008, at 12.
[64] *Larsen B Ice Shelf Collapses in Antarctica,* NAT'L SNOW & ICE DATA CENTER, Mar. 18, 2002, http://nsidc.org/iceshelves/larsenb2002/index.html.
[55] Douglas R. MacAyeal et al., *Catastrophic Ice-shelf Break-up by an Ice-shelf-*

February, probably draining through fissures in the ice.[56] By late February 790 square kilometers of the shelf had disappeared.[57] By early March almost another 2500 square kilometers had disappeared in the same area where the melt water ponds were seen earlier.[58] While the breakup of such ice shelves themselves have little impact on sea level, they are believed to have a major impact on the rate of ice flow off the land as a result of the removal of the buttress blocking their access to the sea, and hence on future sea level rise.[59] New research, however, suggests that Larsen B had been somewhat unstable prior to the collapse due to weak "suture zones" between the contributions of various glaciers that fed it and ice shelf retreat from 1998 to 2000.[60] That does not explain the reasons for the retreat, however, which appear to be related to warming temperatures in the area. It is not at all clear exactly how much or how soon GHG emissions would have to be reduced to prevent other possible ice shelf collapses in Antarctica nor how this might be calculated.

d. West Antarctic Ice Sheet Losing Mass

Very recent research concludes that the West Antarctic Ice Sheet ("WAIS") is also losing significant mass, almost as much as the GIS.[61] West Antarctica is estimated to have lost 132±60 Gt/yr (147±67 cubic kilometers/yr.) in 2006, with losses concentrated in far west Antarctica in glaciers emptying into the Amundsen Sea.[62] The loss on the Antarctic Peninsula is estimated to be 60±46 Gt/yr (67+51 cubic kilometers/yr.) in 2006, and has been concentrated on the east side of the Peninsula. The

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fragmentcapsize Mechanism, 49 J. GLACIOLOGY 22, 22 (2003); Ted Scambos et al., *Climate-Induced Ice Shelf Disintegration in the Antarctic Peninsula, in* ANTARCTIC PENINSULA CLIMATE VARIABILITY: A HISTORICAL AND PALEOENVIRONMENTAL PERSPECTIVE 79,80 (E.W. Domarck et al. eds., 2003); C. J. Van der Veen, *Fracture Propagation as Means of Rapidly Transferring Surface Meltwater to the Base of Glaciers,* 34 GEOPHYSICS RES. LETTERS L01501 (2007).

[56] *Larsen B Ice Shelf Collapses, supra* note 54.

[57] *Id.*

[58] *Id.*

[59] *Id.*

[60] N.F. Glasser & Ted A. Scambos, *A Structural Glaciological Analysis of the 2002 Larsen B Ice Shelf Collapse*, 54 J. GLACIOLOGY 3,14-15 (2008).

[61] Eric Rignot et al., *Recent Antarctic Ice Mass Loss from Radar Interferometry and Regional Climate Modeling*, 1 NATURE GEOSCI. 106, 106 (2008).

[62] *See* Marc Kaufman, *Escalating Ice Loss Found in Antarctica*, WASH. POST, Jan. 14, 2007, at Al.

total is 214±118 cubic kilometers/yr.[63] In both cases this may be due to glacial acceleration, which in turn may be a result of increased ocean temperatures. As in the case of the GIS, attempts to use ERD to prevent a further rise in sea levels from WAIS mass losses would have to based at best on an informed guess.

e. Sea Level Rise

Sea level rise is one of the least controversial effects of global warming and one of the better documented ones. It appears to primarily result from several factors, particularly:

- Melting of the ice sheets in Greenland, West Antarctica, and East Antarctica
- Melting of other glaciers not part of the three ice sheets
- Thermal expansion of the oceans as they rise in temperature.[64]

Given the location of much human infrastructure near sea level, even a small increase in sea level would have some adverse effect. Even a small increase in the risk to New Orleans or Venice is not a desirable outcome. Increased damage is likely first from storms and ultimately from permanent flooding of low-lying areas near oceans. When and if it occurs, humans would either suffer increased storm damage to their infrastructure and the land on which it sits or have to build and maintain massive engineering works to avoid storm flooding. If sea level should continue to rise, the infrastructure and land would probably have to be abandoned as it becomes permanently flooded. Reductions in the disappearance of glaciers from temperate latitudes is likely to result in decreased runoff during the warm months, which decreases the water available for irrigation during those months.

Two researchers have developed a graph showing the 2001IPCC projections of sea level rise and comparing these with actual global sea level rise.[65] It shows an increasing divergence between the two, with a

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[63] Rignot et al., *supra* note 61, at 106.
[64] See A. Cazenave & R.S. Nerem, *Present-day Sea Level Change: Observations and Causes*, 42 REV. GEOPHYSICS 20 (2004).
[65] *Id.*

divergence of more than a centimeter between the two trend lines in recent years.[66]

There is no way to know whether sea level will continue increasing, decrease, or stay the same. But in recent years it has increased at a fairly steady rate according to current information.[67] There would appear to be a credible risk that it will continue to rise if glaciers and polar ice sheets continue to respond to present or possible future warmer polar temperatures and if the oceans continue to experience thermal expansion. Once an ice sheet loses mass it is very difficult, and probably infeasible, to put it back given the huge volumes of ice involved. It would appear to be more efficient to prevent ice sheet mass losses than to attempt to protect valuable infrastructure near sea level in the future. Prudence and economics would suggest early action to at least stabilize sea level. Obviously, if world temperatures and sea level should stop rising, much less would need to be done. But in an ideal world, lowering polar temperatures enough to prevent damage to human infrastructure and resources would probably be a much cheaper way to avoid flood damage than the construction and maintenance of massive engineering works.

As shown in the table below, the previous interglacial period roughly 120,000 years ago is believed to have had roughly a four meter higher sea level and one to two degrees Celsius higher global temperatures. The Pliocene Era, roughly three million years ago, is believed to have had two to three degrees Celsius warmer temperatures and about a twenty-five meter higher sea level. In contrast, in the Eocene Epoch, approximately forty million years ago, sea level was about seventy-five meters higher and temperatures about four degrees Celsius higher, while twenty thousand years ago at the last glacial maximum temperatures were about six degrees colder and sea level about 125 meters lower. All these points form a relatively straight line on a chart, suggesting that the IPCC projection of three degrees Celsius higher temperatures and less than a one meter higher sea level by 2100 are inconsistently much lower than the line.[68] Now this could be because it takes time for sea level to

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[68] *Id.*
[67] *Id.*
[68] David Archer & Victor Brovkin, Millennial Atmospheric Lifetime of Anthropogenic CO_2, Figure 3 (Dec. 6, 2006) (unpublished manuscript on file with Climatic Change and available at http://www.pik-potsdam.de/~victor/archer.subm.clim.change.pdf). The following quotation from the same article suggests that real ice sheets might be able to collapse more quickly than generally realized:

> The forecast for the coming century is for only 0.5-1 meters, in spite of a temperature change of 3° C . . . . The contrast with the data from the

readjust to higher temperatures and that 100 years is too short a time for that adjustment to take place, or it could be that the IPCG underestimated the rise in sea level that might occur by 2100. In any case, it appears credible that sea level will continue to rise unless there is a significant change in global temperatures. For the reasons discussed in Subsection b above, it would be very difficult under an ERD approach to determine how much of a change in emissions would be necessary to stop sea level rise by any specific date.

Sea Level and Global Temperatures by Epoch[69]

	Interglacial periods max. (~120kybp)	Pliocene (Hansen)
Global average temps compared to present (°C)	Hansen (2007) +1 Rohling (2007) +2	+2-3
Sea level compared to present (meters)	Hansen +4±2 Rohling +4-6	+25±10
Max rate of sea level rise (meters/century)	Hansen +5 Rohling 1.6	

3. Inability to Control Other Potentially Dangerous Climate Changes

The long standing concern about El is that there may be a "tipping point" where a continued rise in global temperatures will trigger non-linear,

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> past is that it takes longer than a century to melt a major ice sheet, according to the ice sheet models used to generate the sea level rise forecast. There are reasons to believe that real ice sheets might be able to collapse more quickly than our models are able to account for, as they did during Meltwater Pulse 1A 19 kyr ago . . . or during the Heinrich events ... neither of which are well simulated by models. At any rate, if we consider that warming from CO_2 release persists for hundreds of millennia, we have plenty of time to change sea level. The correlation with the past seems to indicate that we could ultimately raise sea level by 50 meters.

Id. at 5.

[69] E.J. Rohling et al., *High Rates of Sea-level Rise During the Last Interglacial Period*, 1 NATURE GEOSCI. 38,38 (2008); James Hansen et al., *Dangerous Human-made Interference with Climate: A GISS Model E Study,!* ATMOSPHERIC CHEMISTRY & PHYSICS 2287, 2287 (2007) [hereinafter Hansen et al., *Dangerous]*.

self-reinforcing further warming or other dangerous environmental effects beyond those resulting immediately from the temperature rise itself. Numerous scenarios have been proposed.[70] Very recently Tim Lenton of University of East Anglia and colleagues concluded the following after eliciting fifty experts and researching many possibilities:

> Society may be lulled into a false sense of security by smooth projections of global change. Our synthesis of present knowledge suggests that a variety of tipping elements could reach their critical point within this century under anthropogenic climate change. The greatest threats are tipping the Arctic sea-ice and the Greenland ice sheet, and at least five other elements could surprise us by exhibiting a nearby tipping point.[71]

In early 2006 James Hansen of NASA stated, "I will argue that we are near a tipping point, a point of no return, beyond which the built in momentum and feedbacks will carry us to levels of climate change with staggering consequences for humanity and all of the residents of this planet."[72]

The inability of ERD to control some potential abrupt climate changes (Els) is illustrated by two cases:

(a) Hansen et al.'s ice sheet disintegration hypothesis;[73]

(b) The European Union's ("EU") 2°C threshold.[74]

In (a) there is assumed to be a maximum level of 450 ppm CO_2 in the atmosphere and one degree further increase (1.8°C above pre-industrial).[75] Hansen's characterization of the situation may have become more urgent late in 2007, however, since he reportedly revised this maximum level to 350 ppm.[76] Since the current atmospheric level of carbon dioxide is about 383 ppm, there is no way to reduce levels to 350 ppm this century even if

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[70] *See* Carlin, *Global Climate Change Control, supra* note 2, at 1445-80.

[71] Tim M. Lenton et al., *Tipping Elements in the Earth's Climate System,* PROC. NAT'L ACAD. SCI. 1786,1792 (2008).

[72] James E. Hansen, Can We Still Avoid Dangerous Human-made Climate Change? Presentation at New School University (Feb. 10,2006) (transcript available at http://www.columbia.edu/~jehl/newschool_text_and_slides.pdf).

[73] See *generally* Hansen et al., *Dangerous, supra* note 69.

[74] Council of the European Union, Climate Change: Medium and Longer Term Emission Reduction Strategies, Including Targets—Council Conclusions (Mar. 11, 2005), http://register.consilium.europa.eu/pdf/en/05/st07/st07242.en05.pdf.

[75] Hattsen et al., *Dangerous, supra* note 69, at 2306.

[76] Bill McKibben, *Remember This: 350 Parts per Million,* WASH. POST, Dec. 28,2007, at A21.

all GHG emissions stopped today other than that of CO_2, which is very expensive to remove from the atmosphere directly.[77] In reality, emissions have been increasing at an increasing rate. In the EU's scenario (b) there is assumed to be a substantial risk of El if global temperatures exceed two degrees Celsius above pre-industrial levels.[78] Case (b) is a little less strict than (a) since Hansen's maximum further increase of global temperatures of one degree Celsius would be roughly consistent with a 1.8°C increase from pre-industrial levels. Each of these will be discussed in turn in this subsection. These hypotheses are not presented as proven science but rather as illustrations of abrupt climate changes (El) that humans may want to nevertheless take measures to avoid because of their potentially catastrophic results. Even if there may only be a small chance that they would actually occur, it is reasonable to ask how an ERD approach would handle these possibly "worst case" scenarios. Case (a) is somewhat similar to the sea level rise and large scale flooding predicted by some proponents of ERD, such as Al Gore. Case (a) is selected, in part, to represent such predictions because it is more carefully defined and documented, which makes it possible to analyze the feasibility of controlling it using ERD. No case is made concerning the likelihood or reasonableness of case (a). But if (a) is not likely to be controllable using ERD, the use of potential sea level rise as an argument for using ERD would appear to be equally weak. Case (a) is selected as a worst credible case—just the type of case where climate change control would definitely be useful. If ERD could not handle it, its usefulness can be questioned.

a. Hansen et al. Ice Sheet Disintegration Hypothesis

One of the threats, which I will call GIS/WAIS disintegration, has been proposed by a prominent group of American climate scientists, usually with James Hansen as the lead author. Two recent papers on the subject by Hansen et al. both concern the risks from additional global warming as a result of sea level rise due to disintegration of ice sheets in Greenland and West Antarctica. The first paper argues that there are dangerous risks if global temperatures rise more than one degree Celsius above current levels.[79] The second uses data from the last 400,000 years of Earth's history to predict how and why they believe that sea levels

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[77] *Id.*
[78] Council of the European Union, *supra* note 74.
[79] Hansen et al., *Dangerous*, *supra* note 69, at 2306.

may rise significantly over this century and to quantify key parameters, including much higher climate sensitivity to increased CO_2 levels.[80] A third paper summarizes other research showing that the Greenland and West Antarctic ice caps are eroding, including speculation that the resulting sea level rise could be as much as five meters by 2100.[81] *New Scientist* describes the consequences of such a possible increase as follows:

> Without mega-engineering projects to protect them, a 5 meter rise would inundate large parts of many coastal cities—including New York, London, Sydney, Vancouver, Mumbai, and Tokyo—and leave surrounding areas vulnerable to storm surges. In Florida, Louisiana, the Netherlands, Bangladesh and elsewhere, whole regions and cities would vanish. China's economic powerhouse, Shanghai, has an average elevation of just 4 meters.[82]

Hansen et al. believe that the most likely and most critical of these dangerous effects is the possibility of substantial sea level rise due to the breakup of parts or all of the ice sheets covering Greenland and West Antarctica. Taken together, Hansen et al. paint a rather alarming forecast of what they view as the dangerous effect of global warming.[83] Their words could not be much more graphic or stark in their description of the risk they believe we face:

> Our concern that [business as usual greenhouse gas] scenarios would cause large sea-level rise this century ... differs from estimates of the IPCC (2001,2007), which foresees little or no contribution to twenty-first century sea level raise from Greenland and Antarctica. However, the IPCC analyses and projections do not well account for the nonlinear physics of wet ice sheet disintegration, ice streams and eroding ice shelves, nor are they consistent with the

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[80] Hansen et al., *Climate Change and Trace Gases,* 365 PHIL. TRANSACTIONS ROYAL SOC'Y 1925 (2007) [hereinafter Hansen et al., *Climate Change]*.

[81] James Hansen, *Scientific Reticence and Sea Level Rise,* 2 ENVTL. RES. LETTERS 024002 (2007) [hereinafter Hansen, *Scientific Reticence]*.

[82] James Hansen et al., *Climate Catastrophe,* NEW SCI. July 28,2007, at 30,34 [hereinafter Hansen et al., *Climate Catastrophe]; see also* Hansen, *Scientific Reticence, supra* note 81.

[83] Hansen et al., *Dangerous, supra* note 69; Hansen et al., *Climate Change, supra* note 80; Hansen, *Scientific Reticence, supra* note 81.

> palaeoclimate evidence we have presented for the absence of discernable lag between ice sheet forcing and sea-level rise.[84]

Hansen et al. say ominously, " [Civilization developed and constructed extensive infrastructure, during a period of unusual climate stability, the Holocene, now almost 12,000 years in duration. That period is about to end."[85]

As summarized in the quotes above, Hansen et al. are arguing that the IPCC failed to take into account several non-linear factors that they believe will result in a much more rapid disintegration of the GIS and WAIS, which will result in a much more rapid than predicted rise in global temperatures due to the resulting decreased albedo.[86] Only by taking into account these factors, they argue, is it possible to explain the observed changes in climate over the last 400,000 years of repeated ice ages. They point out that the terminations of each of the ice ages during this period occurred very rapidly and that this observation needs to be taken into account in any explanation.[87]

As of mid-2007, Hansen et al., however, believed that their concerns could still be met through reductions in emissions of both CO_2 and the other GHGs, but they did state that they believed we were then at the outer limits of what can still be done to prevent the catastrophe that they predict would otherwise occur.[88]

Hansen's argument can be summarized as follows: Excess heat is largely going into the oceans, and some into the atmosphere. Warming oceans thin or destroy ice shelves. When this happens, glaciers accelerate when their "plug" is pulled. Ice shelves have been observed breaking up on the Antarctic Peninsula and the Arctic.[89] Melting glaciers create meltwater that lubricates glacial movement and decreases albedo on surface.[90] Summer melt has increased in Greenland and West Antarctica.[91] The

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[84] Hansen et al., *Climate Change*, *supra* note 80, at 1950.
[85] *Id.* at 1944.
[86] *Id.*
[87] *Id.* at 1946-48.
[88] *Id.* at 1950.
[89] *Larsen B Ice Shelf Collapses*, *supra* note 54.
[90] Some new research supports some aspects of this hypothesis. See Dorothy K. Hall et al., *Greenland Ice Sheet Surface Temperature, Melt and Mass Loss: 2000-06*, 54 J. GLACIOLOGY 81, 91 (2008).
[91] Hansen et al., *Climate Change*, *supra* note 80, at 1936.

threat is that West Antarctic and Greenland ice sheets will disintegrate. The result would be a rapid and large rise in sea level (seven meters in the case of Greenland alone).[92] The problem he sees is that human infrastructure located near sea level is vulnerable.[93]

Hansen et al. predict a catastrophic rise in sea level if temperatures rise more than 1.8°C over pre-industrial levels but claim that by stringent regulation of CO_2 and the trace GHG gases it is still possible to avoid it.[94] However, they do not explain exactly how this actually can be done. The immediate question is whether their claims are credible that emissions controls could be sufficient to solve the sea level rise threat they perceive. This is where a recent paper by Rive et al.[95] is particularly relevant. Rive et al. generate emissions scenarios based on various temperature targets.[96] However, they ultimately conclude that any achievable temperature target is not a useful tool for regulation given the uncertainty of climate sensitivity.[97] The larger question is whether the world should plunge ahead with a reliance on ERD given that the risk of catastrophe appears to be very large according to Hansen et al.'s analysis and the costs very high as well.

If Hansen et al. are correct, the ERD strategy proposed by many environmental groups, California, some Western European governments, and some members of Congress, would appear to be rational only if ERD could avoid dangerous climate changes. If not, this approach is likely to result in the dangerous global climate changes about which these groups/ governments and the UNFCCC are most concerned. The four new papers discussed above taken together suggest that ERD is not just ineffective and inefficient, but may also not be a feasible approach to avoid ice sheet disintegration given Hansen's assumptions.[98] Hansen et al. are arguing that the real climate sensitivity is roughly double[99] that assumed by the IPCC,[100] which would bring it to about six degrees Celsius for a doubling

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[92] Julian A. Dowdeswell, *The Greenland Ice Sheet and Global Sea Level Rise*, 31 SCIENCE 963, 963 (2006).
[93] Hansen et al., *Climate Catastrophe, supra* note 82.
[94] Hansen et al., *Dangerous, supra* note 69, at 2306.
[95] Nathan Rive et al., *To What Extent Can A Long-Term Temperature Target Guide Near-Term Climate Change Commitments?*, 82 CLIMATIC CHANGE 373, 385-87 (2007).
[96] *Id.* at 378-81.
[97] *Id.* at 385.
[98] See *infra* Appendix 1, Case 3.a.
[99] Hansen et al., *Climate Change, supra* note 80, at 1944.
[100] INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE, CLIMATE CHANGE 2007: SYNTHESIS REPORT, SUMMARY FOR POLICY MAKERS 21 (2007) [hereinafter IPCC SYNTHESIS REPORT] .

of CO_2. The implementation feasibility diagrams presented by Rive et al. show that the use of a two degrees Celsius temperature limit above pre-industrial temperatures and a six degrees Celsius sensitivity lies so far outside the implementation possibilities they found as to be unachievable.[101] The important point of this subsection is that ERD appears highly unlikely to be able to avoid a GIS/WAIS disintegration such as the one that Hansen has hypothesized. This subsection is not intended to argue when or whether such an ice sheet disintegration may occur—only that ERD would be powerless to avoid it if it would otherwise happen according to Hansen's hypothesis.

b. Inability to Meet the European Union's 2°C Goal

In the second case, the threat/goal is derived from the UNFCCC and the announced policy by the EU as to how it should be implemented. The ultimate goal of climate change control, the UNFCCC has declared, is to avoid Els.[102] This has generally been interpreted as a temperature ceiling that if observed would accomplish this. The EU has explicitly adopted a limit of two degrees Celsius above pre-industrial levels[103] and Germany, Britain, and Sweden have implicitly accepted it.[104] These four Western European jurisdictions have all proposed implementing it, however, in ways that are unlikely to achieve the two degrees Celsius limit,[105] possibly because they appreciate the difficulty of meeting it. California, however, has used the limit as the basis for its climate change control legislation,[106] as have some of the bills that have been proposed in Congress.[107] The history and scientific basis for the two degrees Celsius limit is briefly summarized by Hansen et al.[108] and more extensively by Rive et al.[109] Others have also suggested that a two degrees Celsius warming is not likely to be safe.[110]

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[101] Rive et al., *supra* note 95, at 382, Fig. 6; *see also infra* Appendix 1, Table 1.
[102]\Council of the European Union, *supra* note 74, at 2 (The EU's goal is to "prevent dangerous anthropogenic interference with the climate system").
[103] *Id.*
[104] George Monbiot, *The Rich World's Policy on Greenhouse Gas Now Seems Clear: Millions Will Die*, GUARDIAN, May 1, 2007, at 29.
[106] *Id.*
[106] California Global Warming Solutions Act of 2006, CAL. HEALTH & SAFETY CODE § 38500 (Deering 2008).
[107] Global Warming Pollution Reduction Act, S. 3698, 110th Cong. (2006).
[108] Hansen et al., *Dangerous, supra* note 69, at 2304-05.
[109] Rive et al., *supra* note 95, at 376.
[110] See *generally* J.B. Smith et al., *Vulnerability to Climate Change and Reasons for*

Rive et al. analyze a range of possible limits on the rise in global temperatures to determine the near-term emission reductions needed to realize them using a variety of climate change parameters.[111] This section primarily uses their methodology as a framework by which to assess the feasibility of an emissions control approach to global climate change control in terms of limiting temperature increases to the levels specified in each of the two threat/goal scenarios just outlined.

Even if climate sensitivity to increased CO_2 is what the IPCC says it is, the modeling work by Rive et al. suggests that it would not only be risky but also very expensive to actually achieve the two degrees Celsius limit using ERD.[112] They find that to obtain a mere fifty percent chance of preventing more than a two degrees Celsius increase would require a global cut of eighty percent from current industrial emission levels by 2050 at a marginal cost of $3,500 per ton of carbon equivalent assuming average projections and "early action" to reduce GHGs.[113] $3,500 is roughly an order of magnitude higher than most previous estimates of marginal costs,[114] presumably reflecting the extremely high cost of rapidly replacing most of the energy producing and using capital stock. An eighty percent cut would imply a reduction per person of about eighty-seven percent below current levels because of predicted world population growth.[115] This appears of very doubtful practicality, particularly at the extremely high marginal costs estimated by Rive et al., and has a mere fifty percent chance of "success" even in the "ideal" world of modeling. This suggests that in the real world a serious effort to achieve such cuts would be extremely

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Concern: A Synthesis, *in* CLIMATE CHANGE 2001: IMPACTS, ADAPTATION, AND VULNERABILITY (J.J. McCarthy et al. eds., 2001); WILLIAM HARE, WBGU-BERLIN, ASSESSMENT OF KNOWLEDGE ON IMPACTS OF CLIMATE CHANGE—CONTRIBUTION TO THE SPECIFICATION OF ART. 2 OF THE UNFCCC 89 (2003), *available at* http://www.wbgu.de/wbgu_sn2003_ex01.pdf; ARCTIC CLIMATE IMPACT ASSESSMENT (ACIA), IMPACTS OF A WARMING ARCTIC: ARCTIC CLIMATE IMPACT ASSESSMENT (2004).

111 Rive et al., *supra* note 95, at 378-85.

112 Mat 383-87.

113 *Id.* at 385; *infra* Table 1. 1.8 gigatons of carbon equivalent ("GtCeq") is about eighty percent of year 2000 emissions. In this and all their other cases, Rive et al. assume that there will be no overshooting because they believe that overshooting might compromise the overall objective. *Id.* at 378. Their term " 'overshoot' refers to when a scenario exceeds a given target (i.e., temperature) for a short period of time as a result of climate system inertia, before eventually returning to the target level." *Id.* at 378 n.3. *See also infra* Table 1.

114 Carlin, *Global Climate Change Control, supra* note 2, at 1452.

115 Alan Carlin, *Risky Gamble,* ENVTL. L. F., Sept-Oct. 2007, at 42,44 [hereinafter Carlin, *Risky Gamble]*.

expensive, require worldwide cooperation and an early start, and be much more likely to lead to catastrophe than success. Worst of all, it would probably postpone serious efforts to develop other approaches that would be more likely to succeed. Rive et al. furthermore find that if we wait an additional ten years to implement serious emissions reductions, a fifty percent chance would not be achievable at all, again assuming "average" projections.[116] For a seventy-five percent probability (which would seem the least that humans might want to aspire to given the stakes involved) and early action, the researchers find that the target of two degrees Celsius is also not achievable.[117] A seventy-five percent probability could be achieved if one accepts "low" projections, but still at a very high marginal cost ($1,400 per ton of carbon equivalent).[118] It appears very unwise, however, to gamble the fate of the world's climate on the lowest projections. It may be unwise to gamble it even on "average" projections. Using a "high" estimate, however, the best that can be achieved is a twenty-five percent probability at a marginal cost of $3,500 per ton of carbon equivalent, according to Rive et al.[119] The apparent implication is that, even under a two degrees Celsius limit and three degrees Celsius sensitivity, ERD is a very long shot with little real hope of meeting the two degrees Celsius limit even before taking into account the wide gap that is almost certain to exist between what is actually achieved and what countries and their citizens may agree to do.

A recent study by Weaver et al. concluded that attempts at reducing GHG emissions (even ninety percent cuts below present levels) would not avoid breaking of the two degrees Celsius "threshold" sooner or later.[120] This further confirms the research discussed above.

There is a great danger that the world will attempt to make enormous economic sacrifices only to suffer all the adverse effects. In other words, even if the world decides to greatly reduce GHG emissions and proves willing to pay the enormous costs involved, there is little or no guarantee that it will not also have to pay for the economic damages that are believed to result from global warming. If the GHG reductions actually achieved (not the reductions promised by various politicians) should fall

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[116] Rive et al., *supra* note 95, at 385 tbl.2.
[117] *Id.*
[118] *Id.* at385 tbl.l.
[119] *Id.*
[120] Andrew J. Weaver et al., *Long Term Climate Implications of 2050 Emission Reduction Targets*, 34 GEOPHYSICAL RES. LETTERS L19703 (2007), *available at* http://climate.uvic.ca/people/alvaro/Emi_2050.pdf.

short of what would ultimately prove necessary to avoid abrupt climate changes (Els) this is a likely outcome if the GHG hypothesis of GW is correct. The unfortunate result would be that the world would pay twice and receive very little"benefit. If, on the other hand, the ERD GHG emission reduction should prove to be more than what would be needed, the world will waste very large resources that could be utilized for other worthwhile purposes but might at least avoid dangerous climate changes. Neither outcome would be very satisfactory, but the first would clearly be worse than the second. Unfortunately, the first currently appears more likely given the likelihood that any ERD approach would not be fully implemented if the GHG hypothesis is correct.[121]

Time may or may not be short. Based on current information the IPCC appears overly conservative in its Arctic projections. Hansen et al. have argued that there is really already 0.6°C more warming already locked into the warming pipeline.[122] If Hansen should prove to be correct, the world only has a margin of 0.4°C[123] not already locked in before reaching his limit—perhaps twenty years at recent rates according to his analysis. If the EU is right, we only have 0.6°C not already locked in according to Hansen's analysis.[124] And on matters of such import, we might be wise not to push our luck. Getting the world to agree to anything in say a few years is next to impossible. Even if they did, implementation would be a major problem. And even if it were not, the needs are almost certain to change.

Global warming (or possibly even cooling) will occur if Earth's energy balance is not stabilized. If this is not achieved, catastrophes are a credible possibility. New Orleans could even turn out to be a minor blip compared to what may happen in the future. Nature's balance of energy that flows into and out of the Earth is very precise since nature does not fudge, as humans are sometimes inclined to do. Furthermore, the system creating this balance is very complicated and changing with major uncertainties. It needs ongoing fine adjustments, not inflexible, internationally negotiated "planning" goals formulated decades in advance using models that will never be able to take into account the full complexity of the Earth's climate system.

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[121] See *infra* Section I.D.

[122] James Hansen, Is There Still Time to Avoid Dangerous Anthropogenic Interference with Global Climate?, Presentation at the American Geophysical Union, Chart 22 (Dec. 6, 2005), *available at* http://www.columbia.edvi/~jehl/keeling_talk_and_slides.pdf.

[123] 1.8°C minus 0.8°C (already realized) minus 0.6°C (already in the pipeline). See *id.*

[124] 2°C minus 0.8°C (already realized) minus 0.6°C already in the pipeline according to Hansen. *Id.*

There are many technical uncertainties. In time, Hansen may prove to be right or wrong or even partially correct. But it appears credible that he could be right, so do we want to risk a catastrophe with ERD? Two degrees Celsius may or may not be the "tipping point." But should we accept at best a fifty percent probability of avoiding it using ERD if it is? The IPCC may be right or wrong in their climate sensitivity estimate. But are we so sure that sensitivity is less than or equal to 3.1°C to risk using ERD? The Arctic (or even the world) may or may not continue warming. But the potential consequences if it does are so serious that we may not want to risk it. *Prudence is to select a control approach that will handle all major credible risks, particularly if costs are very much lower. ERD is not such an approach,* although it may be able to make a contribution if its limitations are understood and if it is used where such remedies can be justified for other reasons.

4. Can Have Major Adverse and Other Environmental Effects

Two new studies published in 2008 in *Science* conclude that when all the effects of growing biofuels are taken into account all biofuels studied result in greater GHG emissions than using petroleum-based fuels.[125] Since biofuels have a variety of adverse environmental effects, the decision to subsidize biofuels in the United States and elsewhere, appears to be an example of the unintended consequences of ERD programs where politicians are prone to select winners rather than leaving the choice to markets. Even if regulations are written to require that certain particularly harmful biofuels not be subsidized, the same result still may occur because the increase in world prices for other biofuels results in the diversion of land to these other biofuels. This further results in the expansion of acreage devoted to the particularly harmful biofuels, as well, at the expense of other environmental values.

Even if biofuels contributed to a reduction in GHG emissions, they may have important adverse environmental effects that would exceed any benefits from the reduced use of other fuels. Increased use of biofuels can also have adverse non-environmental effects. Examples include the expansion of oil palm plantations at the expense of rainforests and driving

[125] Joseph Fargione et al., *Land Clearing and the Biofuel Carbon Debt*, SCI. EXPRESS, Feb. 7 2008, at 1235-36; Timothy Searchinger et al., *Use of U.S. Croplands for Biofuels Increases Greenhouse Gases Through Emissions from Land Use Change*, SCI. EXPRESS, Feb. 7, 2008, at 1238-39.

up prices for food particularly in countries where food represents a major proportion of household expenses.[126] Even where efforts are made to avoid the expansion of particularly harmful biofuels production, there may be adverse spillover effects into other agricultural products that can serve as substitutes for those whose use as biofuels is being expanded. Greater use or proposed use of corn for biofuels appears to have already resulted in higher prices for corn[127] and the substitution of some other product for other uses which may have adverse environmental or other effects.

Another example of trading off decreased emission of GHGs for other environmental risks is provided by the possibility that expanded nuclear power could be substituted for fossil fuel-based energy sources.[128] As demonstrated by Chernobyl and Three Mile Island, however, there may be major environmental risks in such a substitution.[129] Given the necessary role that must be played by politicians in any ERD approach, it is not unlikely that radically increasing biofuel use may not be the last unintended adverse effect of ERD use.

5. Uncertainties Concerning GHG Hypothesis Do Not Justify Large Investments in ERD Until They Are Better Resolved

There are many reasons for not pursuing the current push to control climate change by using ERD, but one of the fundamental reasons is that we simply do not know enough and may never know enough to sufficiently and accurately predict that the actions proposed would solve the problem. As discussed in introductory Section C above, it is becoming increasingly clear that there may be some additional factors influencing global temperatures beyond those considered by the IPCC. It is too early to reach definite conclusions, but it may also be too early to invest in ERD for the sole purpose of reducing impacts on humans (E2) or avoiding abrupt climate changes (Els) to the extent that it cannot be justified on other

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[126] Food prices have risen substantially recently, which some believe is due in part to in creased use of biofuels. See *The New Face of Hunger*, ECONOMIST, Apr. 19,2008, at 32-34, as well as other related articles in the same issue. For a discussion of the adverse environ mental effects of palm oil expansion, see Elizabeth Rosenthal, *Once a Dream Fuel, Palm Oil May Be an Eco-Nightmare*, N.Y. TIMES, Jan. 31, 2007, at Cl.

[127] *The New Face of Hunger*, *supra* note 126.

[128] Patrick Moore, *Going Nuclear: A Green Makes the Case*, WASH. POST, Apr. 16, 2006, at B01.

[129] *Anniversary Lessons from Three Mile Island and Chernobyl*, ENVT. NEWS SERVICE, Mar. 26, 2004, http://www.ens-newswire.com/ens/mar2004/2004-03-26-03.asp.

grounds besides GW reduction. Some emissions reductions can be justified in terms of improved national security[130] and profitable increases in energy efficiency.[131] But, if it turns out that there are other significant factors (such as variations in the Sun's magnetic field or other characteristics) that explain some of the GW in the late twentieth century, there appears to be a significant risk that investments in ERD justified only for the purpose of GW reduction may be partially or even entirely wasted. Scientific consensus about uncertain effects does not prove scientific validity.

The proponents of ERD argue that whatever the uncertainties in the significance of GHGs in explaining climate change, it is imperative that we start a serious ERD program immediately because of the long period required for it to become effective in reducing the growth of atmospheric GHGs. As will be discussed in Section III below, however, there is an alternative approach that does not require a long period to become effective, so there is little risk in terms of El and E2 involved in waiting until the evidence becomes clearer as long as the alternative is developed to the point that it could be used in an optimized form if it should be needed.

B. Inflexibility—Inability to Respond Rapidly to New Information and Circumstances

Because all international ERD approaches currently under consideration require that GHG emission reduction targets be established far in advance, often ten to even forty years in advance, and because of the difficulty of rapidly changing these targets if international agreements must be renegotiated on the basis of new information, it is very safe to conclude that ERD would have difficulty responding rapidly to new circumstances or research information.[132] As outlined in introductory Section C above, however, such new information is coming forth all the time, and in some cases appears to be of great significance with regard to what GHG emission reductions would appear to be necessary.

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[130] Such as by reducing dependence on imported energy supplies consistent with the economic value of the resulting improvement in natural security. See Marc A. Levy, *Is the Environment a National Security Issue?* 20 INT'L SEC. 35 (1995).

[131] Some believe that significant increases in energy efficiency can be profitable. *See, e.g.*, JON CEEYTS ET AL., MCKINSEY & COMPANY, REDUCING U.S. GREENHOUSE GAS EMISSIONS: HOW MUCH AT WHAT COST (2007), *available at* http://www.mckinsey.com/clientservice/ccsi/pdi7US_ghg_final_report.pdf.

[132] If a cap-and-trade approach was used to implement ERD there could be moderately rapid changes within those countries adopting such an approach. The problem arises in changing the control goals between nations in response to new information or circumstances.

Suppose, for example, that a Kyoto follow-on protocol is eventually agreed upon that involves significant reductions in GHG emissions by almost all nations and is eventually by ratified by all these nations. Suppose it later develops that the agreed upon reductions are much too small to avoid major dangerous effects of global warming or there is unforeseen rapid warming in the Arctic or the agreed upon goals are not fully implemented. Under these circumstances it would appear very difficult to rapidly repeat the international negotiation process to avoid the resulting adverse effects.

On the opposite side, suppose that the sun enters a period similar to the Dalton minimum[133] in the next few years, and temperatures start plunging just as they did during the Little Ice Age. And suppose that the world had just agreed on a very ambitious program of ERD controls. Would those who worked so hard to bring this about be willing to admit that the sun does play a major role in the Earth's climate and that ERD was only making cooling worse? Would they further recommend that all the ERD controls be abandoned immediately and that most expenditures for GHG control to that date had made the situation worse rather than better? I doubt it.

Now, although these two scenarios are not implausible, they may be somewhat unlikely. But there actually is a strong expectation that at least one very significant climate forcing factor will change, and there is always a possibility that others will as well. The expectation relates to major volcanic eruptions, which often put sulfate particles into the stratosphere, and have the effect of decreasing the solar radiation received on Earth for a period of a year or more following the eruptions.[134] During such eruptions, humans need a warmer rather than a cooler Earth if crop losses and other adverse effects of cooling are to be avoided. ERD would be less than helpful in this regard since, if effective, it would presumably make the world even colder than it otherwise would have been.

In summary, there are many circumstances where the inflexibility of ERD would make it very counterproductive in terms of solving either El or E2. There are even plausible circumstances where ERD would make these problems worse, not better.

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[183] The Dalton Minimum was a period of low sun spot activity occurring between the 1790s and 1820s. K. Mursula et al., *Geomagnetic Activity During the Dalton Minimum: New Evidence for the Lost Cycle,* 5 GEOPHYSICAL RES. ABSTRACTS 10,361 (2003).
[134] Carlin, *Global Climate Change Control*, *supra* note 2, at 1424-27, 1476.

C. Extremely Expensive

The marginal cost of implementing ERD programs depends both on the objectives sought as well as on the climate sensitivity assumed. As discussed in Section I.A.3(b) above, Rive et al. show that it would be extremely expensive and quite risky to avoid a two degrees Celsius threshold for abrupt climate changes (Els) by using ERD assuming commonly accepted sensitivity factors.[135] More ambitious objectives are either not achievable or would be even more costly.[136] An earlier paper found that, although there may be some low cost or even free partial remedies, efforts to substantially reduce emissions would be very expensive.[137] Table 1 at the end of the main text presents a brief summary of the costs of using ERD. It assumes that the objective of using ERD would be to avoid abrupt climate changes (E Is) by keeping temperatures from increasing more than two degrees Celsius from pre-industrial levels. It also assumes current assumptions as to the climate sensitivity factor.

D. Politically Unrealistic

ERD places heavy demands on the political systems where it would be implemented. There are strong economic incentives not to reduce GHG emissions. These incentives could be changed by governmental action, but they are so fundamental that this would prove to be difficult, as illustrated by the problems many EU countries and Canada have found in meeting their commitments under Kyoto,[138] politicians would be required to maintain unusually strong resolve as the population learns what would be the real effects of the measures. Under current circumstances, politicians can argue that higher energy prices are a result of the operation of the laws of supply and demand. But if markedly higher prices or energy use restrictions were imposed for the purpose of reducing global warming, they would face a tougher situation.

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[135] Rive et al., *supra* note 95, at 385.

[136] The cost of controlling Els using ERD under two assumptions is discussed in some detail *supra* Section I.A.3.

[137] Carlin, *Global Climate Change Control*, *supra* note 2.

[138] Andrew Osborn, *EU Nowhere Near Meeting Kyoto Targets*, THE GUARDIAN, Dec. 3, 2003, at 13. Friends of the Earth sued Canada for failing to uphold its obligations under Kyoto. Dianne Saxe, *Kyoto Violations Could Be Costly to Canada*, RECORD (Kitcher-Waterloo, Ontario), Dec. 18, 2007, at A9.

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 constituents would not pursue every available loophole rather than reduce their welfare and freedom of choice. Global warming has all the psychological characteristics—a long time horizon, uncertainty, and few readily apparent effects to remind people that there is a problem in their everyday lives—needed to keep it at a modest level of priority, even with a huge public education campaign.

ERD appears to be politically unrealistic for three reasons: (1) The proposed GHG reductions are highly unrealistic; (2) they are unlikely to be successfully implemented; and (3) the goals are unrelated to people's normal experience.

1. Proposed GHG Reductions Highly Unrealistic

A number of the ERD bills currently in the U.S. Congress require an eighty percent reduction in GHG emissions, usually compared to 1990, and often by 2050.[139] With more than twenty-five percent increases in world energy use emissions between 1990 and 2004,[140] this would require reductions of over eighty-four percent from current levels. With projected population growth, this would require about an eighty-nine percent reduction in emissions per person worldwide even ignoring economic growth.[141] Another way of looking at this problem is the reduction in energy use thought to be needed to achieve the goals of this proposed legislation. Even when future economic growth is left out of the calculation, global energy efficiency per person would have to be increased by roughly eighty-nine percent or human services provided by energy use reduced by eighty-nine percent per person, or some combination of the two.[142] Energy efficiency can be increased, but only slowly, and at considerable cost for the more aggressive measures.

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[139] *See, e.g.*, Climate Change and Energy Bills Introduced in the 110th Congress, Heritage Foundation, http://www.heritage.org/research/energyandenvironment/upload/bg2075_table.pdf (last visited Apr. 4, 2008).

[140] U.S. ENERGY INFO. ADMIN., REPORT NO. DOE/EIA-0573, EMISSIONS OF GREENHOUSE GASES REPORT (2007), awziZa&fe orf http://www.eia.doe.gov/oiaf/1605/ggrpt/ttglobal (under "US Emissions in a Global Perspective").

[141] Assuming world population of 6.371 billion in 2004 and 9.393 billion in 2050, based on current population projections of the U.S. Bureau of the Census, International Database, http://www.census.gov/ipc/www/idb/ranks.html (last visited Apr. 4, 2008).

[142] Carlin, *Risky Gamble, supra* note 115, at 44.

Alternatively, the use of energy services could be reduced, either voluntarily or by government mandate. This would probably be even more difficult. The rapid growth in energy services seems likely to overwhelm any other savings. More computers, more server farms, and more cell phones appear to be quite likely by 2050, to take only a few examples of likely increased energy use services.[143] One proposal for reducing such services, for example, is to reduce per capita average vehicle-miles traveled from 10,000 annually to 5,000 through better urban design, mass transit, and telecommuting.[144] But to entice drivers to forgo half their trips would require monumental incentives; the more likely prospect is non-achievement, or possibly coercion. The even more drastic proposal for individual emission rationing reported to be under consideration in Great Britain a few years ago is a logical extension of the ERD approach,[145] but it is difficult to see how it would attract much support. While increased energy efficiency may eventually contribute significantly, the deep cuts in energy services that would appear to be required to reduce total emissions by eighty-nine percent per person worldwide are politically unrealistic. In fact, they are highly unrealistic.

Meeting the goals of these proposals using ERD is either impossible, or very expensive and risky, assuming the current estimates of needed reductions (we do not really know, however, which reductions are needed because we cannot reasonably determine the climate sensitivity factor in advance). The limited experience to date is that those jurisdictions with some of the most active energy conservation programs, such as California and Britain, have been roughly holding their own in recent

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[143] See ENERGY SAVING TRUST, THE AMPERE STRIKES BACK: HOW CONSUMER ELECTRONICS ARETAKINGOVER THE WORLD 3 (2007), *available at* http://www.sustenergy.org/UserFiles/File/ampere_strikes_back.pdf (projecting that by 2020 combined consumer electronics and the information and communication technology sectors are expected to use forty-five percent of the electricity used in British homes excluding electric heating).

[144] Stephen W. Pacala & Robert H. Socolow, *Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies*, 305 SCIENCE 968, 970 (2004). This particular proposal would probably only reduce GHG emissions if the users actually reduced their miles traveled by any means resulting in GHG emissions rather than using mass transit. A new study argues that rail transit uses more energy per passenger mile and that many generate more GHGs than the average passenger automobile, and that buses are even less efficient. Randal O'Toole, *Does Rail Transit Save Energy or Reduce Greenhouse Gas Emissions*, CATOINST., Apr. 14, 2008, at 1.

[145] See David Adam, *Swipe-Card Plan To Ration Consumers'Carbon Use*, GUARDIAN, July 19, 2006, at 10, *available at* http://www.guardian.co.uk/climatechange/story/0,,1823853,00.html.

years—i.e., a reduction of zero percent.[146] Given economic and population growth and the proliferation of energy use services, this may be the most that could actually be achieved by ERD. Even if more can be achieved in particular countries, it would not approach the eighty-four percent needed on a worldwide basis according to a number of the proposed bills. Except under special circumstances, such as the collapse of Eastern European industry after 1989,[147] most countries have experienced a gradual increase in emissions, and some are growing rapidly.[148] Most less developed countries have also been unwilling or unable to participate in emission cuts.[149] More than governmental cooperation would be needed. The idea that all the people of the world would cooperate to make something this effective happen is extremely unlikely.

A new study summarizes the situation as follows:

> If we wish to reduce CO_2 emissions to 80 percent below 1990 levels, whether U.S. or global, we are faced with three alternatives: radically restrict our energy use, most likely through strict rationing; reduce our population by two-thirds; or, invent or intensively develop low-carbon, carbon-neutral or carbon-negative sources of energy, such as geothermal, tidal and nuclear power. The third option has numerous technical and political sticking points, but it is the only one which does not require a culture and economy more rigorously policed than those of the centralized command systems of the old Soviet Union and People's Republic

[146] Between 1990 and 1999 California GHG emissions increased slightly according to Terry Surles, California Energy Commission, Presentation at Kyoto Japan: California Activities Addressing Greenhouse Gas Emissions (Oct. 1, 2002), *available at* http://energy.ca.gov/pier/papers_presentations/2002-l~24_Gas-Emissions.ppt. United Kingdom CO_2 emissions based on the more comprehensive environmental accounts basis have shown little change between 1990 and 2005 according to NATIONAL AUDIT OFFICE, UK GREENHOUSE GAS EMISSIONS: MEASUREMENT AND REPORTING (2008), *available at* nao.org.uk/publications/0708_greenhouse_gas_emissions.pdf.

[147] Matthew Wald, *Carbon Dioxide Emissions Dropped in 1990, Ecologists Say,* N.Y. TIMES, Dec. 8, 1991, at 17.

[148] For a list of each country's carbon emissions, see Carbon Dioxide Emissions (CO_2), Metric Tons of CO2 Per Capita, Millennium Development Goals Indicator, http://mdgs.un.org/unsd/mdg/seriesDetail.aspx?srid=751&crid= (last visited Apr. 4, 2008).

[149] *See* James Kanter & Andrew C. Revkin, *Binding Emissions Treaty Still a Possibility, U.S. Says,* N.Y. TIMES, Feb. 27,2008, *available at* http://ww.nytmes.com/2008/02/27/world/europe/27climate.html?_r=l&ref=europe&oref=slogin; OECD, OECD ENVIRONMENTAL OUTLOOK TO 2030: SUMMARY IN ENGLISH 6 (2008), *available at* http://www.oecd.org/dataoecd/29/33/40200582.pdf.

> of China. In short, technology is the only feasible and humane means to both reduce greenhouse gas emissions and maintain an acceptable standard of living.[150]

Others are less optimistic as to how feasible even the technological approach may be.[151]

The situation may actually be much worse since anthropogenic emissions may eventually have to be reduced to zero if the adverse effects of GW are to be avoided. According to Pierre Friedlingstein's writing in *Nature*, "[T]o stabilize climate the concentration of greenhouse gases in the atmosphere must be stabilized, and to do so . . . anthropogenic emissions will eventually need to be reduced to zero."[152] Professors H. Damon Matthews and Ken Caldeira agree: "Our results suggest that future anthropogenic emissions would need to be eliminated in order to stabilize global-mean temperatures."[153] Unfortunately, most scholars believe that this is a practical impossibility in the modern world. Matthews and Caldeira disagree. Caldeira claims, "It is just not that hard to solve the technological challenges. We can develop and deploy wind turbines, electric cars, and so on, and live well without damaging the environment."[154] Although it may or may not eventually prove theoretically possible to eliminate carbon emissions through advanced technology, the cost of doing so both economically and politically make this an unattainable goal. The idea that developing countries, can or actually would, undertake such a drastic technological change when they now object to doing anything to reduce GHG emissions is not realistic.

The obvious question, if these three authors are correct that emissions reductions would have to approach zero, is whether it is even worth starting down the ERD path for reducing El and E2? Partial reductions in GHG emissions may do no harm, but if they ultimately will not solve

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[150] *Considerations for an 80% Reduction in Carbon Dioxide Emissions*, MARSHALL INST. POL'Y OUTLOOK, Jan. 2008, at 6, *available at* http://www.marshall.org/pdfymaterials/572.pdf.

[151] See *generally* Martin I. Hoffert et al., *Advanced Technology Paths to Global Climate Stability: Energy for a Greenhouse Planet*, 298 SCIENCE 981 (2002).

[152] Pierre Friedlingstein, *A Steep Road to Climate Stabilization*, 451 NATURE 297, 298 (2008).

[153] H. Damon Matthews & Ken Caldeira, *Stabilizing Climate Requires Near-Zero Emissions*, 35 GEOPHYSICAL RES. LETTERS L04705 (2007).

[154] Press Release, Carnegie Inst. for Sci., Stabilizing Climate Requires Near-Zero Emissions (Feb. 15,2008), *available at* http://www.ciw.edu/news/stabilizing_climate_requires_near_zero_carbon_emissions.

El and E2, other approaches would have to be used in the end anyway. So why start unless it is justifiable on other grounds?

2. Unlikely to Be Successfully Implemented

ERD assumes that every nation, including most people and other entities in these nations, will cooperate with emission reduction goals established through some sort of voluntary international agreement. This appears very unlikely given the history of voluntary international cooperation between nations.[156] If only a few economically significant nations do not cooperate or actively enforce whatever ERD plan may be agreed upon, the eighty percent reductions would have to be increased even more in the remaining countries in order to achieve the worldwide reductions now being proposed. And if even one economically significant nation does not cooperate or does not implement effective enforcement, there is likely to be a movement of high GHG emitting industries from countries that do cooperate to those that do not, with a resulting loss of jobs and income, and strong political opposition by those displaced. Even the threat of effective GHG reductions and enforcement thereof is likely to result in serious political opposition and probably retreat by the governments involved.[157] Since a substantial share of GHG emissions reductions would have to occur as a result of individual and corporate actions to either reduce energy services or to make energy use more efficient, the results would also substantially depend on individual and corporate decision-making (as well as any other economic entity or local government entities responsible for energy use decisions). National governments can change the incentives for energy use decisions, but are largely powerless in democratic countries to change individual, corporate, and other entity behavior if such behavior does not respond to governmental incentives. An immediate question is how strong of incentives that democratic governments would be willing to impose. Since the effects of price increases would appear to most citizens as a kind of tax increase, politicians are likely to have a strong aversion

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[155] See Carlin, *Global Climate Change Control*, *supra* note 2, at 1431-45 (providing more detail on some of these points).
[166] *Id*. at 1442-43.
[157] This process appears to be starting in Europe in early 2008 as a result of proposals by the European Union to require Europe's steel, chemical, and power sectors to buy permits for their GHG emissions. See *EU Ready to Cut Energy-Intensive Industries Some Slack from Climate Change Package*, INT'L HERALD TRIB., Feb. 21,2008, *available at* http://www.iht.com/articles/ap/2008/02/21/business/EU-FIN-EU-Climate-Change.php.

to such incentives.[158] Even if a nation agrees to a particular GHG reduction goal, that does not guarantee that the nation will actually achieve this goal. In fact, many if not most participating Annex I countries in the Kyoto Protocol appear unlikely to meet their commitments.[159] Another example is the protection of intellectual property; many nations have agreed to protect it, but some nations provide much more effective protection than others do.[160] Even if all governments agreed to voluntary international standards for GHG emissions, different governments would be likely to implement them in different ways, which would probably have widely varying results. There is no obvious reason why the results would be any more effective in reducing GHG emissions than the Kyoto Protocol. They might well be less since many less developed countries would have to be involved, which presumably have less capability to bring about actual energy use reductions than the participating Annex I nations.

Recent fossil fuel emissions have not been very encouraging despite all the worldwide discussion of reducing GHG emissions. In fact, depending on the data source used, emissions have been higher than or equal to the most pessimistic scenarios proposed by the IPCC in the period 2004 to 2006.[161]

Finally there are the already apparent disagreements between the developed countries and the less developed countries over GHG emissions control. Since almost every country would have to participate in order to make the controls effective (based on current knowledge and assumptions, of course), the less enthusiastic countries would have to be persuaded to implement such controls. This could be done either through direct international agreements or by example. The problem with the example approach is that once a country or group of countries have "led by example" they would have much less bargaining power in any international negotiation, while their example would not have sufficient effect on total worldwide emissions to solve the climate change problems.

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[168] For a real life example of this see Jonathan Oliver, *Tories Ditch Green Taxes*, SUNDAY TIMES (London), Feb. 24,2008, *available at* http://www.timesonline.co.uk/tol/news/politics/article3416624.ece.

[159] Carlin, *Global Climate Change Control, supra* note 2, at 1431.

[160] See *U.S.: China Has High Rate of Intellectual Property Infringement*, WASH. FILE, Apr. 29, 2005, http://usinfo.state.gov/usinfo/Archive/2005/Apr/29-580129.html (noting several countries that are listed on the U.S. Trade Representative's "priority watch list" for intellectual property rights violations).

[161] For 2004 to 2005 data see Michael R. Raupach et al., *Global and Regional Drivers of Accelerating CO_2 Emissions*, 104 PROC. NAT'L ACAD. SCI. 10,288, 10,289 (2007) (relying on Figure 1). For added data points for 2005 to 2006 data, see Schrag Presentation, *supra* note 7, at 20.

3. Goals Unrelated to People's Normal Experience

One reason that ERD would be likely to experience great difficulty is that the effects experienced by the average person are likely to remain difficult to ascertain and measure by the average person. Many in temperate climates may even welcome warmer temperatures because of the increased number of warm days each year. If objectives are defined as parts per million of atmospheric CO_2 or a reduction in the rate of growth in GHG emissions, these objectives are well beyond the capability of most people to either understand or measure. With no such readily apparent benchmarks, most people would tend to discount the risk and as a result may be less than willing to make sacrifices to achieve them. Politicians who may propose such sacrifices are not likely to be popular either. This problem with using ERD will be discussed in much more detail in Section II below.

E. Summary of Reasons Why ERD Would Be Unlikely to Prevent Dangerous Climate Changes

This Article does not argue for or against the widely accepted GHG hypothesis of the cause of GW. Rather, it argues that there is substantial uncertainty and that even if the hypothesis is correct and the currently accepted parameters of climate sensitivity are correct that ERD is highly unlikely to be able to solve El and E2. It further argues that ERD is not an effective or efficient means to do so. Unfortunately, current knowledge does not allow us to determine the accuracy of the hypothesis. But if the GHG problem is not as serious as many currently believe, there is also less reason to pursue GHG reductions than currently believed.

If changes in GHG levels are a significant factor in GW, there would be a great danger of attempting to make enormous economic sacrifices using ERD only to suffer all the adverse effects. Because of the problems outlined in Section I, global warming would continue until Earth's energy balance was stabilized. Catastrophes might occur—New Orleans might prove to be only a very minor blip if the GIS or WAIS continue to melt. This balance is very precise—nature does not fudge. The system creating this balance is very complicated and has major uncertainties. It needs frequent fine adjustments, not inflexible, internationally negotiated "planning" goals formulated far in advance. It requires the cooperation of most nations, corporations, and people to be implemented successfully. ERD has important similarities to economic central planning, but probably worse—world central planning without world government. Voluntary international agreements such as are now proposed have not always been successful; examples include the Kyoto Protocol and the Kellogg-Briand Treaty. The latter committed the signatories not to use war as an instrument of national policy.

On the other hand, if the GHG hypothesis is not a significant explanation of GW pursuit of ERD would not control temperature increases or avoid dangerous climate changes. It would simply waste resources (except when justified for other reasons) reducing GHG emissions that could be more efficiently used for other purposes and postpone the time when effective action would be taken to solve these problems.

Finally, if GHGs are less of an influence on climate than the IPCC believes, reducing atmospheric GHGs would have lower benefits and would not be as effective at preventing abrupt non-linear climate changes (El) and climate change's direct effects on temperatures (E2) as the IPCC predicts. Given all the problems implementing ERD, it would probably be better to use a control approach that influences or counteracts the other factors that influence El and E2.

More generally, the GHG hypothesis of GW may or may not prove to be a significant explanation for GW. Since there is an alternative approach[162] that can be used to control El and E2 rapidly and at much lower cost, there is little to be gained by rushing to a decision until the science becomes clearer. Hansen may prove to be right or wrong. We do not currently know enough to judge. But it appears credible that he could be right; so do we want to risk a catastrophe by using ERD to solve a problem that it apparently could not solve? Two degrees Celsius may or may not be an important "tipping point."[163] But should we accept at best a fifty percent probability of avoiding this "tipping point" using ERD?[164] IPCC may be right or wrong in their estimate of climate sensitivity. But are we sure enough that sensitivity is 3.1 °C to risk using ERD?[165] *Prudence is to select a control approach that will handle all credible risks, particularly if costs are much lower. ERD is not such an approach.* There is a great danger of making enormous economic sacrifices to reduce GHG emissions only to suffer all the adverse effects if either the effects of GHG emissions have been underestimated or if future possible agreements upon goals for

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[162] *See generally infra* Section III.
[163] Council of the European Union, *supra* note 74, at 2.
[164] See Rive et al., *supra* note 95, at 385.
[165] IPCC, SYNTHESIS REPORT, *supra* note 100, at 21.

GHG reductions are not realized. It is possible, of course, that if ERD is pursued that every country would pursue the most cost-effective remedies first with high payoffs in terms of improved national security and profitability as well as in GHG reductions, so that the losses might be minimized. Given the experience with bio-fuels to date, however, just the opposite may occur too since politics, not economics, may prevail.[166]

II. NEW GOALS NEEDED DIRECTLY RELATED TO EFFECTS PEOPLE UNDERSTAND

For a number of years, climate change control has been understood as a single problem with a single solution. The widely proposed solution has been to reduce GHG emissions, whether by implementing an enhanced Kyoto Protocol, various proposals by Al Gore, or various bills in Congress.

A much more useful description of the problem is that when the Earth is warming it is receiving more radiation energy than it is losing, which is the basic cause of increasing global temperatures.[167] This energy is stored in various reservoirs: oceans, land, and atmosphere.[168] If not corrected either by man or nature, it is possible that the climate system may get "out of control" with unknown but probably catastrophic consequences. The solution is to bring Earth's radiation balance into equilibrium. The most important question is where that equilibrium should be. From an economic viewpoint, the answer is the level that maximizes the net economic benefits of control. Unfortunately, we have only a limited understanding of many of the economic benefits of control, so this definition may be difficult to implement. This section will explore some of the more practical alternatives.

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[166] See *supra* Section I.A.4; *see also* James R. Healey, *E85 Does Poorly in Cost-Benefit Analysis*, USATODAY, Nov. 30,2007, at 7A (publishing research that shows that E85 fuel is less cost-effective than diesel). Despite this evidence, the U.S. Government supports the proliferation of ethanol fuels. For example, President Bush signed the Energy Policy Act of 2005. A press release announcing the signing stated that "[t]he bill includes a flexible, cost-effective renewable fuel standard that will double the amount of ethanol and biodiesel in our fuel supply over the next seven years." Press Release, White House, President Bush Signs Energy Policy Act (Aug. 8,2005), http://www.whitehouse.gov/news/releases/2005/08/20050808-6.html.

[167] *Finds Increasing Solar Trend That Can Change Climate*, NASA, Mar. 20, 2003, http://www.nasa.gov/centers/goddard/news/topstory/2003/0313irradiance.html [hereinafter *NASA Study]*.

[168] WILLIAM KININMOUTH, CLIMATE CHANGE: A NATURAL HAZARD 77 (2004); James Hansen et al., *Earth's Energy Imbalance: Confirmation and Implications* 308 SCIENCE 1431 (2005).

In addition the acidity of the oceans has been rising due to higher atmospheric CO_2 levels.[169] The solution to the ocean acidity problem is to either bring down CO_2 levels or to find ways to directly change ocean pH levels.[170]

A. Basic Problem: Earth's Radiation Imbalance

Until radiation balance is achieved, global temperatures will increase or decrease. A chart (Figure 1) prepared by NASA's Goddard Institute for Space Sciences (currently headed by James Hansen) shows the major factors, or "climate forcings" as the physicists call them, that they believe are influencing the radiation balance.[171] It should be noted that this chart shows greenhouse gases as a very strong and rapidly increasing forcing factor, consistent with Hansen's views.[172] For the reasons discussed in Section I.C and II.A.1 above, this depends critically on a number of assumptions, which may or may not prove to be accurate. But it does present a simple way of looking at some of the major factors thought to influence GW.

All attempts to reduce global warming must change one of these forcings if they are to be successful. Almost all proposals to do so have involved reducing the forcing resulting from greenhouse gases (the top line in Figure l(a)) through ERD. Decreasing GHG levels in the atmosphere should indeed decrease the net climate forcing, although the extent is unclear. An alternative is to find ways to reflect more of the incoming radiation to the Earth back into space before it reaches Earth[173] through SRM using added aerosols in the stratosphere (the bottom jagged line in Figure l(a)).[174] Both would push climate forcings towards equilibrium when global temperatures are rising.

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[169] ROYAL SOC'Y OCEAN ACIDIFICATION DUE TO INCREASING ATMOSPHERIC CARBON DIOXIDE vi (2005), *available at* http://royalsociety.org/displaypage.doc.asp?id=13539.
[170] *See id.* at 37.
[171] *See infra* Figure 1.
[172] *See id.; see also* James Hansen et al., *Climate Forcings in the Industrial Era*, 95 PROC. NAT'L ACAD. SCI. 12,753, 12,757 (1998).
[173] Altering Earth's radiation balance has been discussed by scholars and climate experts since 1979. Carlin, *Global Climate Change Control*, *supra* note 2, at 1447.
[174] *See infra* Figure 1. Figure 2(b) *infra* clearly shows the effects of the increased stratospheric aerosols resulting from major volcanic eruptions on global temperatures. SRM as discussed in the Article would simply enhance this effect. For a discussion of using aerosols to reflect solar radiation see Carlin, *Global Climate Change Control*, *supra* note 2, at 1459-63; Paul Crutzen, *Albedo Enhancement by Stratospheric Sulfur Injections: A Contribution to Resolve a Policy Dilemma?*, 7 CLIMATIC CHANGE 211,212 (2006); T.M.L. Wigley,A *Combined Mitigation I Geoengineering Approach to Climate Stabilization*, 314 SCIENCE 452 (2006).

B. Where to Balance Forcings?

A very interesting question is how to select the extent to which the climate forcings should be reduced. For a number of years, GHG control advocates attempted to determine the GHG emission reductions on the basis of their computations using prevailing assumptions as to climate sensitivity of the reductions needed to keep global temperatures from exceeding a specified increase from pre-industrial levels, usually two degrees Celsius.[175] As this has become increasingly difficult to achieve with rising atmospheric GHG levels, the objective appears to have been transformed into percentage reductions of GHG emissions by a specified year.[176] Since such reductions should really be means rather than ends, however, there is no obvious justification for this. As mentioned, the economic ideal is to maximize the net economic benefits of control. Benefits are very hard to measure due to varying views by different groups of people and the need to assume a climate sensitivity as well as the usual measurement problems encountered in any effort to determine economic benefits. But if this is difficult or even practically impossible to determine, then one interesting possibility is to explore measurable objectives corresponding to each major effect of global warming to see if there are some useful ones. Since the costs of control using SRM are very small and largely fixed,[177] the degree of control should depend almost entirely on the benefits of various levels. Different countries and people will have different benefits for different temperatures. Trying to balance all that using formal economic analysis would be very difficult and beyond our current capabilities. Benefits of temperature stabilization are very hard to measure due to varying views and the need to assume a climate sensitivity as well as the usual measurement problems.

There are basically two ways to balance climate forcings. Humans could decrease GHG concentrations in the atmosphere or reflect more of the incoming radiation back into space.[178] Decreasing GHG concentrations would decrease heat retained by the Earth and, thus, lower global temperatures. But this is likely to be only a very long-term solution since many GHGs remain in the atmosphere for a very long time,[179] and, unless they

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[175] See Council of the European Union, *supra* note 74, at 2.
[176] *See, e.g.*, Regional Greenhouse Gas Initiative, http://www.rggi.org/ (last visited Apr. 4, 2008).
[177] See Carlin, *Global Climate Change Control*, *supra* note 2, at 1496.
[178] See *id.* at 1414-15.
[179] See National Oceanic and Atmospheric Administration, Greenhouse Gases: Frequently Asked Questions, http://lwf.ncdc.gov/oa/climate/gases.html (last visited Apr. 4, 2008).

are removed from the atmosphere, the GHG forcing will also continue for a very long time. If, on the other hand, more incoming radiation is reflected back into space the heat balance of the Earth can also be balanced. This can be done, for example, by using SRM.

As mentioned above, the objectives of climate change control are now generally discussed as GHG emissions reduction percentages from a specified date or CO_2 or CO_2 equivalent levels. These are abstract concepts completely outside the experience/knowledge of most people. They depend on climate sensitivity, which is not knowable in advance[180] and not directly related to the outcomes sought.

Although there are technical difficulties, a better approach would appear to be to change the focus to major effects rather than difficult abstractions. With sufficient effort these can all probably be accurately determined, unlike climate sensitivity or even GHG emissions. It appears best to concentrate on actual objectives related to effects on which there is relatively little room for argument. The effect would be to emphasize them rather than GHG emissions and CO_2 levels. Examples of these objectives include global average temperatures, sea level, and ocean pH. This would focus attention on the critical objectives.

By looking for possible goals associated with these three principal effects or problems, it may be possible to identify better objectives or goals for climate change control.

1. Global Average Temperatures

Global temperatures are of critical importance because of their potential effects on non-linear climate changes (Els), as well as their direct effects on humans and ecosystems (E2s). If temperatures should be stabilized, the risk of Els will be reduced but not eliminated. At the very least they would be postponed. Temperature is a useful objective which people can observe (but with difficulty). One difficulty with its use is that there is no agreement on how to measure global average temperatures, and there are significant differences between measurements.[181] But there is not likely to be much agreement between countries and peoples as to desired levels. Some would prefer warmer weather and a few colder.

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[180] *See supra* Section I.A.1.

[181] See Watts, 4 Sources Say, *supra* note 18, for a link to recent data from four of the major indices.

2. Sea Level Change

Sea level rise may or may not prove to be the most dangerous aspect of climate change, but it does follow temperatures so stabilization should prevent temperature rise.[182] Although there are some difficulties measuring it and other factors influencing sea level may need to be taken into account,[183] it is an economically important damage from climate change[184] that could provide a very sensitive guide to the optimum level for incoming radiation from the sun. Importance and degree of progress would be reinforced every time there is a major storm/event resulting in coastal flooding. It is very difficult to reverse a rise once it has occurred; by far the best approach appears to be prevention, so there is a strong argument for early action to adjust sea level to an advantageous level.

Rising sea levels endanger any infrastructure (such as cities) humans have built near sea level, as well as access to natural resources (such as farmland) located at such levels. Substantially decreasing global temperatures risks a new ice age[185] which would endanger any infrastructure and resources in the path of advancing ice sheets.[186] Although it is not possible to accurately define the magnitude or probability of these two risks, they may well represent the major economic risks associated with climate change. What remains is a narrow band of temperatures near those of the current interglacial period; the net economic benefits of control are likely to be maximized by staying within this narrow band. If the objective of climate policy is to stay within this band, humans will need some practical objective for accomplishing this. One possible such physical objective might be no rise in temperature or sea level (or possibly a little lowering of temperatures or sea level), but no substantial loss either. This would keep the world out of a new ice age and also prevent flooding of land and cities now near sea level.

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[182] Sea level rise is largely due to thermal expansion of oceans and glacial and ice cap melt. See *supra* Section I.A.2.e.

[183] For the difficulties in measuring sea level, see Carl Wunsch et al., *Decadal Trends in Sea Level Patterns: 1993-2004*, 20 J. CLIMATE 5889, 5890 (2007). For some of the other factors that may be influencing it see B.F. Chao et al., *Impact of Artificial Reservoir Water Impoundment on Global Sea Level*, SCI. EXPRESS, Mar. 13, 2008.

[184] Erica L. Plambeck et al., *The Page 95 Model: Integrating the Science and Economics of Global Warming*, 19 ENERGY ECON. 77, 83 (1997).

[185] WILLIAM F. RUDDIMAN, PLOWS, PLAGUES, AND PETROLEUM 95-105 (2005).

[186] *Id.; see also* JEAN M. GROVE, THE LITTLE ICE AGE 69-71 (1988) (noting the damage caused to farmland in Norway by the advance of the Jostedalsbreen ice sheet between 1680 and 1750).

3. Ocean pH Levels

Important ocean ecosystems involving calcifying organisms, such as coral reefs, have developed under current ocean pH levels and show considerable sensitivity to these levels.[187] Increasing atmospheric CO_2 levels threaten to increase these pH levels (E3), although the exact effects are uncertain. Ocean pH is measurable and an important objective, but it would be very difficult to observe or raise public concern about something they cannot see and are unlikely to understand very well.

In considering whether to abandon ERD as the proposed solution, an important issue concerns the problem of ocean acidification, the third of the three principal climate change effects that the world may wish to address, and which cannot be addressed using SRM. The Royal Society has expressed considerable concern about the fate of coral reefs and other sea life containing calcium carbonate in acidifying oceans.[188] Caldeira has stated that the reefs and other organisms can really only be saved by avoiding almost any further CO_2 emissions, since he believes any net emissions will have an adverse effect.[189] He has suggested a ninety-eight percent reduction from current emission levels,[190] apparently assuming that other natural forces reducing atmospheric CO_2 levels might counteract the remaining two percent. The Royal Society and Caldeira cite the high cost and practical difficulties of geoengineering approaches toward mitigating the chemical effects of increased atmospheric CO_2 concentrations on the oceans.[191] But as noted, decreasing CO_2 emissions will be a difficult and, at best, a very slow undertaking.[192] Reducing them by ninety-eight percent does not appear to be within the realm of realistic possibility in the current world, and probably falls well outside the bounds of the achievable if Rive et al. were to analyze this case.[193] But Caldeira argues that not reducing CO_2 emissions will result in the extinction of the world's coral reefs.[194] "Surely before this is allowed to happen it would be worthwhile

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[187] ROYAL SOC'Y, *supra* note 169, at 2.
[188] See *generally id.*
[189] See Ken Caldeira, *What Corals Are Dying to Tell Us About CO_2 and Ocean Acidification*, 20 OCEANOGRAPHY 188,195 (2007); see *also* Elizabeth Kolbert, *The Darkening Sea*, NEW YORKER, NOV. 20, 2006, at 70.
[190] *Id.* at 195.
[191] See *generally* ROYAL SOC'Y, supra note 169, at 37; Caldeira, supra note 189, at 195.
[192] See *supra* Section I.D.
[193] See *generally* Rive et al., *supra* note 95.
[194] Caldeira is quoted as stating, "Coral reefs will go the way of the dodo unless we quickly cut carbon-dioxide emissions." Press Release, University of Illinois at Urbana-Champaign, Regardless of Global Warming, Rising Carbon Dioxide Levels Threaten Marine Life (Mar. 8,

to carefully reexamine all available [ocean] geoengineering options, including those rejected by the Royal Society and Caldeira, since these would appear to be the only realistic options available that might satisfy [the Royal Society's and] Caldeira's concerns as to the effects of ocean acidification."[195] More generally, ocean acidification appears to need additional research and probably future action once the problem and solutions to it are better understood.

C. A Practical New Goal

One simple and straightforward approach to bringing Earth's radiation balance into balance would be to aim to adjust incoming radiation[196] so as to prevent any further sea level rise—and perhaps even lowering it slightly so as to reduce the damage done by storms. This could be the economic optimum but may not be. Although careful research would be needed, one possibility might be to control only temperatures in polar regions while leaving the remainder of the world as it would otherwise be to the extent possible.[197] There would presumably continue to be thermal expansion of the oceans in other areas, but that might possibly be balanced by expanding some existing ice sheets. Non-polar glaciers would continue to shrink, but reversing that would require temperature changes in non-polar areas as well, which might be much more controversial but a possible longer term goal.

III. AN ALTERNATIVE APPROACH—SOLAR RADIATION MANAGEMENT ("SRM")[198]

Fortunately, there is an alternative to relying on ERD for avoiding abrupt climate changes (El) and impacts on human populations (E2),

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2007), *available at* http://earthobservatory.nasa.gov/Newsroom/MediaAlerts/2007/2007030824507.html.

[195] Carlin, *Global Climate Change Control, supra* note 2, at 1472-75.

[196] *Id.* at 1414-15; *see also NASA Study, supra* note 167.

[197] This may be effective because studies show that climate change in polar regions is 1.5 to 4.5 times greater than in the rest of the world. M.M. Holland & CM. Bitz, *Polar Amplification of Climate Change in Coupled Models*, 21 CLIMATE DYNAMICS 221 (2003).

[198] For a much more detailed discussion of SRM see Carlin, *Global Climate Change Control, supra* note 2, at 1446-50 and Alan Carlin, *Implementation & Utilization ofGeoengineering for Global Climate Change Control*, 7 SUSTAINABLE DEV. L. & POLY 56, 56-58 (2007) [hereinafter Carlin, *Geoengineering Climate Change]*. The only SRM option considered in this Article is that identified as Remedy G in Carlin, *Global Climate Change Control, supra* note 2, at 1449-50, 1496-97.

although it is almost never mentioned by environmentalists and not widely known, much less understood, by the public: SRM, sometimes called atmospheric geoengineering or engineered climate selection. An extensive review of management strategies and currently available alternative technologies for global climate control reached the conclusion that SRM is the most effective and efficient first step toward solving El and E2 quickly and easily.[199]

SRM would control temperatures by reducing the radiation reaching the earth from the sun (or, in the case of global cooling, increasing the radiation). This could be most easily and reliably accomplished by adding particles optimized for this purpose to the stratosphere to scatter a small, carefully calculated portion of selected wavelengths of incoming sunlight back into space.[200] These particles would naturally slowly drop out of the stratosphere, and would have to be replaced, making relatively rapid adjustments possible. This and similar approaches could be viewed much like any other aerospace project, would cost a tiny fraction of the cost of ERD, would need no public involvement once a decision had been made to proceed, would not require the alteration of lifestyles or standards of living, would provide the flexibility needed to rapidly respond to any warning signs of imminent danger, and would allow an appropriate response in the case of global cooling due to major volcanic eruptions or possible solar variability—thus solving most of the problems of using ERD, except ocean acidification. SRM would also avoid the need for extensive economic and energy planning by leaving GHG emission decisions to the private sector, possibly using an institution patterned on the Federal Reserve Board or International Monetary Fund to make periodic adjustments to incoming solar radiation to achieve the desired global energy balance.

As pointed out by Nobel price winner Paul Crutzen in 2006[201] and the National Academy of Sciences in 1992,[202] there has already been a planet-wide proof of concept: when major volcanic eruptions occur, approximately once a decade, they shoot huge amounts of particles into the air, cooling the planet for several years. One of the best known examples was the explosion of Mt. Tambora in 1815, which caused the "year without a summer" in Europe.[203] The sulfur-containing particles thrown out by

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[199] Carlin, *Global Climate Change Control*, *supra* note 2, at 1464-67.
[200] *Id.* at 1448-50; *see also id.* at 1497-98 (discussing Remedy G).
[201] Crutzen, *supra* note 174, at 212.
[202] *See* NAT'L. ACAD. OF SCI., PANEL ON POLICY IMPLICATIONS OF GREENHOUSE WARMING 448-54 (1992), *available at* http://books.nap.edu/openbook.php?isbn=0309043867.
[203] Carlin, *Global Climate Change Control*, *supra* note 2, at 1425 (citing Shanaka L. de Silva, *Volcanic Eruptions and Their Impact on the Earth's Climate*, *in* ENCYCLOPEDIA OF

eruptions are probably less than optimal.[204] It appears reasonable to believe, however, that humans could substantially improve on nature by refining the type of particles used and minimizing other possible environmental side effects with a little research and development. Crutzen and two co-authors have made a step in that direction by recently publishing an article that explores scenarios involving varying the size of the particles injected and found that particles smaller than those coming from volcanoes may be more efficient.[205]

A. *Comparison with Problems Using ERD*

One obvious question is how SRM would handle the specific problems raised in Section I with regard to using ERD. If SRM has the same problems as ERD, it would not offer much of an alternative. This comparison is briefly summarized in Table 1 at the end of this paper.

1. Technically Risky Aspects of ERD

The first problem discussed in Section I.A in relation to the technical risks of ERD concerns the inability to determine climate sensitivity. The use of SRM does not require any knowledge of climate sensitivity or GHG reductions since no reductions would be made. Global warming would be controlled through reductions in incoming radiation from the sun, not by changing the GHG levels in the atmosphere and, thereby, (if successful) the radiation absorbed by the atmosphere. Atmospheric CO_2 levels and emissions would presumably continue to increase.[206]

The second technical problem with using ERD concerned its inability to prevent further rapid Arctic warming. SRM may be particularly useful in such an endeavor since it could change the incoming radiation levels from the sun within a few weeks after a decision was made to use it.[207] SRM may even be able to restrict its effects primarily to the polar areas if that should be advantageous.

WORLD CLIMATE 788, 788-94 (J. Oliver ed., 2002), *available at* http://www.space.edu/documents/Volcanoclimate. pdf).

[204] NAT'L ACAD. OF SCI., *supra* note 202, at 457.

[205] Philip J. Rasch et al., *Exploring the Geoengineering of Climate Using Stratospheric Sulfate Aerosols: The Role of Particle Size*, 35 GEOPHYSICAL RES. LETTERS LO2809 (2008).

[206] Carlin, *Global Climate Change Control*, *supra* note 2 at 1472.

[207] Scott Barrett, *The Incredible Economics of Geoengineering,* 39 ENVTL. & RESOURCE ECON. 47 (2008) (citing T. Sterner et al., *Natural Disasters and Disastrous Policies,* 48 ENVIRONMENT 20 (2006)).

The third technical problem was the inability of ERD to avoid abrupt climate changes (Els). The percentage reduction in incoming sunlight required to avoid a given increase in global temperatures and the corresponding addition of particles to the stratosphere to achieve this reduction can probably be estimated with moderate accuracy using computer models.[208] But in the worst case, the same result could be achieved by trial and error by starting with very low concentrations and observing the results and changing the number or reflective capabilities of the next group of particles added to the stratosphere when that is required by the slow degradation of the older ones.

The fourth technical problem concerned major adverse environmental and other effects. In this case, the effects would definitely be different, but it is unknown as to whether those resulting from ERD or SRM would be worse. This is primarily because of lack of research in the case of SRM.[209] Because fo the great flexibility in particle placement altitude and latitude, and in particle quantity, size, and type that can be employed using SRM, however, it is difficult to make any definitive statements on environmental impacts until all of these factors have been carefully optimized through research. In the case of ERD, there may have been some lack of interest in carefully analyzing the environmental effects of decreasing fossil fuel use.[210]

The fifth and last technical problem concerned the effect of uncertainties on the justification for undertaking large investments in ERD. Although there is a strong need for development work on SRM, there can be little doubt as to the technical soundness of the approach given the experience over many years with temperature changes after major volcanic eruptions.[211] Less incoming sunlight would result in lower temperatures. There would be a need for a political (preferably international) agreement on a command and control system for using SRM, but it could, if necessary, be carried out by one country with the technical and economic resources to implement it.[212] But once that was accomplished, the system should be

[208] *Id.* at 48.
[209] See *id.* at 48-49 for some possible environmental effects of SRM; see also Eli Kintisch, *Scientists Say Continued Warming Warrants Closer Look at Drastic Fixes*, 318 SCIENCE 1054-55 (2007); Carlin, *Global Climate Change Control, supra* note 2, at 1484-85,1497.
[210] See *supra* Section I.A.4.
[211] Carlin, *Global Climate Change Control, supra* note 2, at 1424-27; *see also* Crutzen, *supra* note 174, at 212 (noting that there was a decrease in temperature of 0.5°C the year following the eruption); *infra* Figure 2.
[212] Barrett, *supra* note 207, at 52-53.

able to respond rapidly to whatever new knowledge and circumstances may occur. In the case of a major volcanic eruption, there would be a need to reduce or eliminate reflecting particles in the stratosphere. If a new ice age appeared to be coming on for whatever reason, the appropriate response would be to substitute particles that would increase temperatures on Earth. Because of the reduced scale trial and error process and the regional implementation possible with SRM because of its rapid response capability and the possibility for selective use at different latitudes, it would no longer be necessary to fully understand Earth's climate system in order to make sound judgments as to what to do (although it would be better to fully understand, of course). Given the uncertainties about the climate sensitivity factor and the significance of GHGs in explaining climate change, the same cannot be said for ERD, where the uncertainties appear likely to undermine any serious attempt to implement it.[213]

2. ERD Inflexibility

Because of the need to replenish the particles in the stratosphere every year or two, SRM would have very great flexibility.[214] In fact, SRM could have as much flexibility as desired by varying the altitude at which the particles are placed, since particles at lower altitudes drop out of the atmosphere more rapidly than those placed at higher altitudes. It could, thus, respond to any change in circumstances or knowledge within a year and possibly less. It could even respond to possible unwanted global cooling, if it should ever occur, by placing different particles in the stratosphere intended to increase world or regional temperatures.[215]

3. Extremely Expensive

SRM is estimated to have a marginal cost about l/10,000th as expensive as ERD per equivalent ton of carbon reduced to limit global temperature increases to 2°C above pre-industrial levels using current assumptions concerning climate sensitivity.[216] Less demanding assumptions as to climate sensitivity or objectives would presumably result in lower marginal costs. This comparison is illustrated in Table 1 at the end of the main text.[217]

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[213] *Supra* Section LA. 1.
[214] *See* Carlin, *Global Climate Change Control, supra* note 2, at 1460.
[215] *Id.* at 1449.
[216] *Infra* Table 2; Rive et al., *supra* note 95, at 385.
[217] *See infra* Table 1.

4. ERD Politically Unrealistic

ERD is politically unrealistic because it places heavy demands on political systems and has strong economic incentives against it.[218] SRM does not place burdens on the political system for enforcement and has lower fixed costs.[219]

The first problem with ERD, cited in Section I under this heading, is that proposed GHG reductions are highly unrealistic. This would not be a problem under SRM since no reductions would be required.

The second problem concerned whether GHG reductions would be likely to be successfully implemented. In the case of SRM, there is little doubt that radiation reductions could be implemented once agreement was reached to do so since it would require only comparatively modest financial but some technical resources.

The third problem related to the lack of understanding by the public of GHG levels or reductions in them. Although SRM would involve changes in levels of stratospheric particles, the goals and evaluation of results would presumably be stated in more meaningful terms such as sea level changes or temperatures, much as the Federal Reserve Board targets inflation and economic downturns. The fourth problem with ERD is political. SRM does not require heavy involvement of political resources and is lower in cost.

B. Other Aspects of the SRM Alternative

SRM would not solve the problem of ocean acidification (E3) in that atmospheric carbon dioxide levels would not be directly affected. ERD would help in theory, but given the impossibility of meeting Caldeira's ninety-eight percent reduction[220] worldwide to prevent the destruction of the world's coral reefs, it may not be a useful solution to this problem either.[221] Fortunately, recent research illustrates that nature has worked out an efficient system for removing carbon dioxide from the seas: fertilizing ocean plankton to stimulate them to absorb carbon dioxide (much as plants do) and transport it to the sea floor.[222] Humans have not yet

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[218] *Supra* Section I.D.
[219] Barrett, *supra* note 207, at 48.
[220] Caldeira, *supra* note 189, at 195.
[221] Carlin, *Global Climate Change Control*, *supra* note 2, at 1473.
[222] *Id.* at 1457-58.

figured out a very efficient way to emulate nature in this regard—seeding the ocean with iron particles has been suggested—but ocean fertilization may be the best current hope, whether under either the ERD or the SRM approach.[223] Given the magnitude of the threat, research on and implementation of geoengineering or other solutions to ocean acidification also needs to become a top priority.

Some scientists have suggested a related strategy: using SRM immediately to bring down temperatures during the long period required to reduce GHG emissions, thus avoiding all the adaptation costs and risks of using regulatory de-carbonization alone, while helping the oceans a bit.[224] This appears to be much more expensive than an SRM approach since extensive de-carbonization expenses would be incurred as well, but it would prevent abrupt climate changes (Els)in the interim, and it is clearly safer than an ERD approach. Others have advocated using SRM as an insurance policy to back up de-carbonization. The problem with this is that very large adaptation and de-carbonization expenses would be incurred in the meantime. And the world may be totally unprepared to use SRM when an emergency arises unless decision-making processes for using it are actively developed and research is carried out to optimize the particles and minimize the environmental effects. This is unlikely to happen unless there are real plans to deploy SRM in the immediate future. Even though any nation with the technical and financial resources could implement such a solution on its own, it would be much better to use an international institution to make decisions on how and when such projects should be undertaken and maintained, given their global impact.[225]

Numerous arguments against SRM have been made, such as the risk of unintended consequences.[226] Certainly there is a need for research to better determine the other environmental effects of SRM. But, although great care needs to be taken in pursuing SRM so as to avoid adverse unintended consequences, it is not often recognized that ERD is also likely to engender unintended consequences, as it already has.[227] There exists an extensive inventory of other arguments for and against various forms

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[223] *Id.*
[224] See Wigley, *supra* note 174, at 452-54.
[225] Carlin, *Geoengineering Climate Change*, *supra* note 198.
[226] See *generally* Jay Michaelson, *Geoengineering: A Climate Change Manhattan Project*, 17 STAN. ENVTL. L.J. 73 (1998) (detailing SRM's pros and cons); see *also* Carlin, *Global Climate Change Control*, *supra* note 2, at 1480-85.
[227] See supra Section I.A.4.

of geoengineering such as SRM, but the issue really turns on a metaphysical question. Even though most GHG control supporters believe that humans are causing major climate changes, they would rather let nature translate human actions in increasing or decreasing GHG emissions into the ultimate effects on climate.[228]

Advocates of SRM and other atmospheric geoengineering approaches, on the other hand, argue that it would be better for humans to determine the desired climatic outcomes (such as lower average temperatures) directly and relatively precisely rather than letting nature, which has no incentive to help humans, sort out the net effects of GHG producing activities. In other words, SRM advocates argue that it is simpler, more direct, and more efficient to attempt to directly determine desired world or regional temperatures rather than trying to guess what GHG reductions might yield the desired temperatures some time in the future, and then trying to implement the reductions.[229] The aim is the same—controlling world temperatures. SRM would do it directly. In the optimistic case an ERD program would first make some educated guesses as to the GHG reductions needed, then try to implement these reductions over a period of many years, then likely revise the estimated reductions needed and try again until it finally got it "right." During this entire time, which could extend over many decades, the world risks abrupt climate changes (Els) if the first try should fail either because of a bad guess as to the reductions needed or because the implementation of these reductions proved ineffective. More research could refine SRM solutions, but ERD supporters generally oppose it,[230] so there is currently no way to find out what the most optimized solutions might be as to where to place exactly what types of particles in the stratosphere.

Humans have advanced as much as they have in no small part because they have used fossil fuel energy to provide services that once depended on animal and muscle power. The way forward is not to turn back the clock but rather to search for and implement solutions to each of the problems posed by global climate change using the best engineering and scientific knowledge in the most effective and efficient manner. Unfortunately, the major effect of relying entirely on the hope of drastically reducing carbon emissions may well be to delay the time when effective action is taken to actually solve the three problems posed by

[228] *See* Carlin, *Global Climate Change Control, supra* note 2, at 1480-81.
[229] *See* Michaelson, *supra* note 226, at 122-30.
[230] Carlin, *Global Climate Change Control*, *supra* note 2, at 1480-85.

global warming. Developing, testing, and deploying refined versions of SRM and determining its environmental effects needs to be a priority, even if it should never be used because possible changes in global temperatures no longer pose any major risks.

Any approach to climate change control needs to be able to handle all credible threats. It needs to be flexible, and to rapidly adapt to new knowledge or circumstances. It needs to be inexpensive enough to minimize damage to the economy but effective enough to protect us. Building, testing, and deploying a workable SRM capability is the best investment we can currently make to control climate change. Unfortunately, we are not taking this modest step, and probably will not, as long as we remain fixated on solutions that demand extensive changes of the world's energy economy.

An alternative to ERD is to increase the negative forcing created by stratospheric aerosols (shown as the jagged line at the bottom of Figure l(a)).[231] There would appear to really be only three basic options and several combinations thereof available for dealing with global climate change: Adaptation, ERD, and SRM/atmospheric geoengineering. My analysis of the Hansen et al. case[232] suggests, however, that ERD is not a useful option for preventing abrupt climate changes (Els), although it can still be helpful. Even if Hansen et al.'s threat analysis of ice sheet disintegration, where global temperatures rise 2°C above pre-industrial limits, is wrong, case 3.b suggests that ERD is still unlikely to be successful in meeting a 2°C temperature limit given average assumptions.[233]

This raises the interesting question of which threat/goal (3.a or 3.b) any control effort should aim to satisfy? Given the nature of the threat, I believe the answer should be the most serious credible threat. In this case 3.a is more serious and credible for the following reason: Suppose ice sheet disintegration (3.a) turns out to be the real threat. If we only do enough to keep global temperatures from rising more than 2°C (3.b), we will have a situation where the world will have spent many trillions of dollars and much valuable time (in the case of ERD) and failed to accomplish the goal of avoiding the real threat. As a result, the world will also have to bear the resulting adaptation costs, such as moving many major cities inland. On the other hand, if we do enough to prevent ice sheet disintegration (3.a), we are also likely to avoid the threats by

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[231] See *infra* Figure 1.
[232] *Supra* Section I.A.3.a.
[233] See *supra* Section I.A.3.b.

preventing global temperature rises (3.b). And if 3.b costs almost as much as 3.a, as is the case with using SRM, the logic is hard to escape. In hindsight we may have spent more than we needed to, but we would have solved the problem and avoided the worst of the catastrophic adaptation costs. Missing the real threat/goal level by even a little may slow the onset of a dangerous climate change, but will not prevent it. This is the nature of the non-linear dangerous climate change threats we face. ERD is particularly ill-suited for avoiding such threats since there will always be political pressure to save a little money, do a little less or even cheat a little in reducing GHG emissions, assuming that worldwide agreement should ever be reached and implemented.

Climate change control needs to have other goals as well, but avoiding abrupt climate changes (Els) is surely the most immediate and critical one. As previously concluded, SRM appears to be the best single option taking all the goals into account.[234] If ERD cannot offer a high degree of assurance of accomplishing the fundamental goal of avoiding a substantial risk of dangerous climatic change, that would appear to leave various other combinations of ERD, adaptation, and SRM as the only remaining options for this purpose.

Although nature long ago demonstrated that there are atmospheric geoengineering options that could be effective in controlling global temperatures[235] and meeting a 1.8°C limit or any other desired temperature limit, no real effort has been made to optimize these options, carefully determine their other environmental effects, nor build an international mechanism for decision making to implement them[236] despite the much lower costs (three to five orders of magnitude) compared to de-carbonization.[237] One country with the required technological and financial resources could, if necessary, implement such a solution directly without involving other countries or people once a decision had been made to proceed.[238] One possibility is a combination of early SRM to avoid any danger of abrupt climate changes (Els) with cost-effective regulatory decarbonization involving increasing energy efficiency but not decreasing energy services. Lack of preparation and support for using SRM approaches may prove to be unfortunate because the result is likely to be expensive but ineffective ERD

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[234] Carlin, *Global Climate Change Control, supra* note 2, at 1486-87.
[235] *Id.* at 1449; Crutzen, *supra* note 174, at 212.
[236] *See generally* Carlin, *Geoengineering Climate Change*, *supra* note 198.
[237] See *infra* Table 2.
[238] Carlin, *Geoengineering Climate Change*, *supra* note 198, at 57; Carlin, *Global Climate Change Control*, *supra* note 2, at 1413-14.

and the threat of catastrophic adaptation. And if Hansen et al. and Caldeira are correct, the resulting adaptation currently appears likely to include adaptation to "dangerous" climate changes and the loss of the world's coral reefs.[239]

The first step towards an effective and efficient response to global climate change is to carefully examine each of the problems posed by global climate change and to determine the best solutions to each problem[240] rather than offering a single panacea (ERD) that appears to have critical limitations as an overall solution. The second step is to carry out the needed development and also to develop a decision-making process for better using SRM. And, the third step is to carefully research and attempt to find workable solutions to ocean acidification, including consideration of the use of ocean geoengineering. Continuing down a path towards ERD, if Hansen et al. are correct, will apparently not avoid dangerous climate changes, or if they are not, would still be very risky, very expensive, and quite possibly disastrous in the end.

CONCLUSIONS

In summary, ERD might be useful for solving the problem of ocean acidification (E3) if that is possible given the extremely stringent requirements believed to be needed to save the coral reefs and other calcifying marine life. It would probably do no harm in solving abrupt climate change (El) and gradual temperature change (E2) problems as long as the problem is GW and not global cooling, but would be unlikely to be of much help either. For global cooling, either as a result of probable large volcanic eruptions or possible solar variability, it would have negative value since it would presumably only make the cooling worse. In order to be useful for GW, it would be necessary to guess decades in advance how much of a GHG emissions reduction would be necessary to precisely meet particular GW reduction targets, despite the daunting problems of successfully implementing voluntary international agreements that are contrary to the short-term self-interest of the nations involved. This would be more a matter of dumb luck than careful planning given the many uncertainties involved. So ERD's main use for these two purposes would appear to be using it when it can be justified for other purposes, such as improving profitability through improving energy efficiency or improving national

[239] *See* Caldeira, *supra* note 189, at 194.
[240] See *generally* Carlin, *Global Climate Change Control, supra* note 2.

security. Depending on ERD for controlling El and E2 would be very expensive and risky and would probably delay more effective and vastly less expensive measures using SRM.

So what to do? The highest priority seems to be to immediately develop an SRM capability to handle any immediate temperature-related effects, possibly first for use in polar areas, when and if they should appear dangerous or advantageously handled by SRM. The needed development work includes optimization of particle quantity, size and type, particle placement by altitude and latitude, determination of other environmental effects, building a command and control capability, and making the legal changes needed to insure that the entity involved could not be sued for damages resulting from climate changes. There also appears to be a need to greatly increase research on indicators of GIS and WAIS disintegration and on causes of and solutions to the problem of ocean acidification. In addition, it would appear reasonable to carry out those components of regulatory de-carbonization that can be justified on other grounds, such as national security or profitability. Other aspects of regulatory de-carbonization might reasonably be postponed until we can be assured that they would have a reasonable probability of achieving effective and efficient global climate change control. There is little doubt that SRM can be used to regulate global, and possibly even some more regional, temperatures whether or not global warming is caused primarily by GHGs or by a solar variability, or both. Regardless of whether temperatures may increase or decrease in the future, this would appear to be a very useful technology to have available for human use, particularly if there should be any threat of a new ice age.

More generally, the world appears to be faced not only with the possibility of catastrophic losses but also with great uncertainty. Wisdom would seem to be to build a highly flexible global climate change control approach that can handle all of the major risks inexpensively and with a high probability of success. The global warming problem currently appears to be worse than the IPCC reports reflect in terms of Arctic warming. ERD appears highly unlikely to provide a practical solution to the possibility of dangerous climate changes and certainly not an economically efficient one. SRM or SRM with regulatory de-carbonization justifiable on other grounds appears to be the best and probably the only real alternative. SRM requires some development, funding, and a legal change, none of which has started. Both ERD and SRM need to be implemented with great caution given the unknowns and the unintended adverse effects that could result. Such unintended effects are much more likely if SRM is delayed until a possible emergency when the emphasis will be on speed rather than unintended effects. Halting sea level rise would be a more useful objective than trying to reduce GHG emissions by a specified amount, in part, because we do not know what reductions might be required and appear unlikely to find out until it is too late to use ERD. Sea level rise also appears to be a more useful and understandable objective. Research is needed, however, on the relationships between this and other possible goals. SRM will not solve the ocean acidification problem, which needs additional research and probably future action once the problem and the solutions to it are better understood.

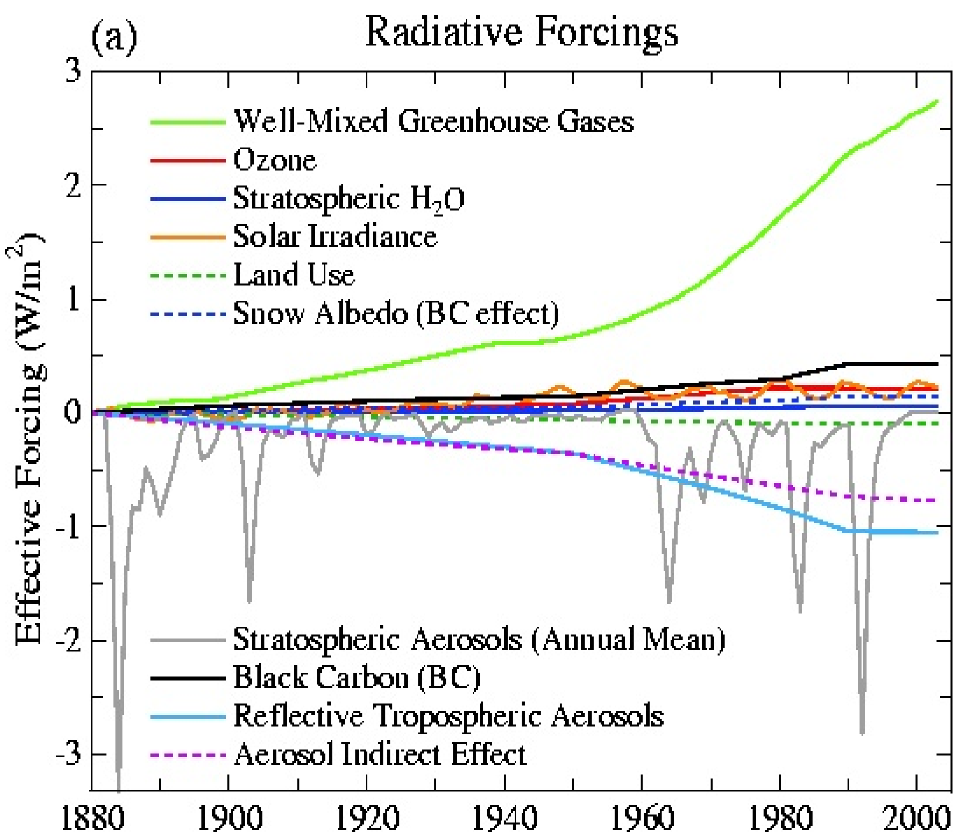

Figure 1(a): Effective global climate forcings over time since 1880.[241]

[241] Goddard Institute for Space Studies, Datasets & Images, http://data.giss.nasa.gov/modelforce/ (last visited Apr. 4, 2008).

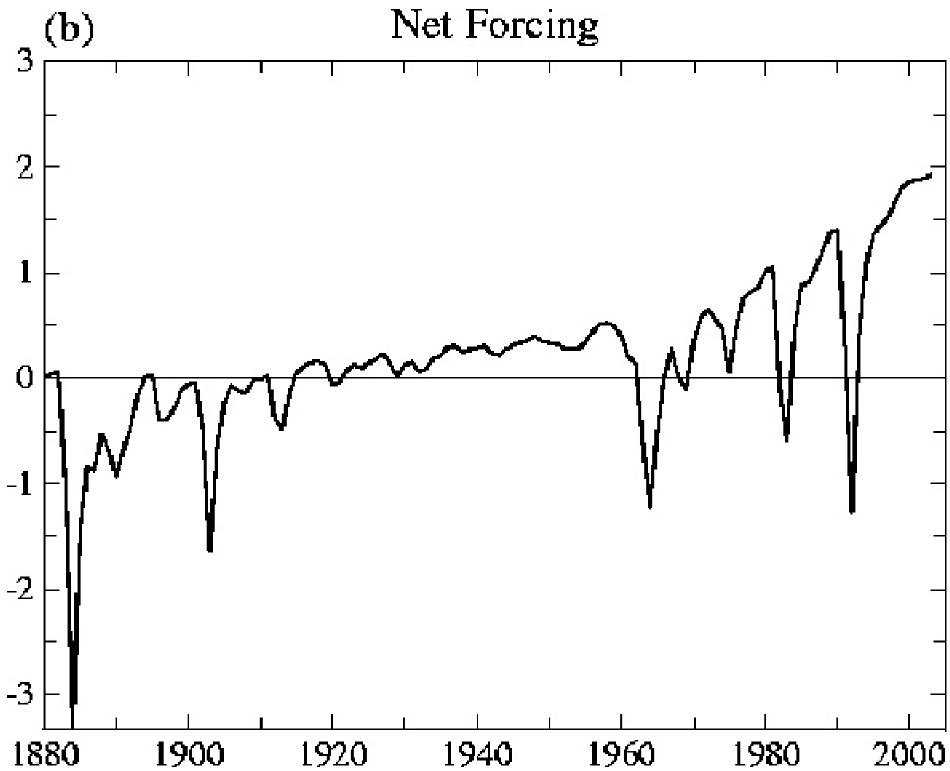

Figure 1(b): Net value of effective global climate forcings over time since 1880[242]

[242] *Id.*

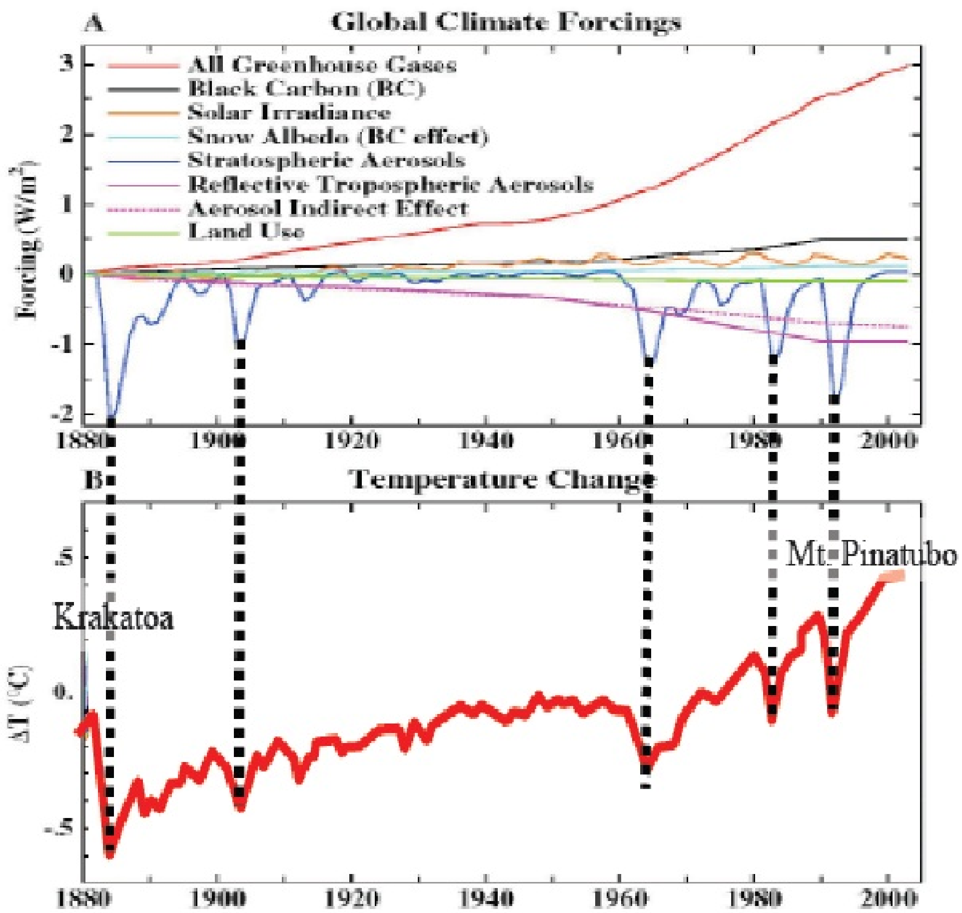

Figure 2: Relation of stratospheric aerosol forcings to global temperature changes.[243]

[243] Chart is a modified form of one used by Jim Hansen. *See* Jim Hansen, Global Warming: Is There Still Time to Avoid Disastrous Human-Made Climate Change? i.e. Have We Passed a 'Tipping Point,' Presentation at the National Academy of Sciences (Apr. 23, 2006), (Presentation available at http://www.columbia.edu/~jeh1/nas_24april2006.pdf). The modifications are intended to make the temperature data more legible and the timing of major volcanic eruptions clearer. The eruptions that have not been identified are the following: 1902: Santa Maria, Soufriere, and Pelee; 1963: Agung; and 1982: El Chichon. The temperature data are the surface temperature observations shown by Hansen in his original figure.

Table 1: General Comparison of SRM and ERD Approaches[244]

Control approach	SRM	ERD
Time to modify	Months to year or 2	Decades
Ability to handle uncertainties	Very great	Very limited by need for new international negotiations
Dangerous changes (E1s)	Capable of fully avoiding	50% probability at best of achieving less than 2˚C increase[245]
Ocean acidification (E3)	No effect	Reduce w/difficulty, not solve[246]
Marginal cost/ton carbon	\$0.02 to 0.10	\$3,500 to achieve 2˚C w/50% probability[247]
Overall costs	Development total \$$10^9$ Annual \$$10^9$	R&D >>\$5 x \$$10^9$ per year[248] Control >>\$135 x \$$10^9$ per year[249]
Effectiveness	Very high	Probably very low
Other environmental effects	Unknown and untested but likely	Some already evident like rainforest destruction from oil palm expansion
Participation needed	Government involvement desirable initially; not required	Active by most governments, companies, and people

[244] Based on Carlin, *GlobalClimate Change Control*, *supra* note 2, unless otherwise stated.
[245] Rive, et al., *supra* note 95 tbl. 1. This assumes a goal of staying below a 2˚C temperature increase from pre-industrial levels in order to avoid dangerous climate changes as per European Union policy.
[246] See discussion *supra* Section II.B.3.
[247] Rive et al., *supra* note 95.
[248] According to Table 8 of the FISCAL YEAR 2007 REPORT TO CONGRESS ON FEDERAL CLIMATE CHANGE EXPENDITURES (2007) *available at* http://www.whitehouse.gov/omb/legislative/fy07_climate_change.pdf, US Government Climate Change Science and Technology Programs alone were about \$4.5 billion in recent years. This excludes all privately funded US R&D and all foreign R&D. Some was for R&D on effects rather than control, however. \$5 billion appears to be a safe lower limit worldwide for control portion of expenditures.
[249] *See* SELECT COMMITTEE ON ECONOMIC AFFAIRS, HOUSE OF LORDS, H.L. 12-I, THE ECONOMICS OF CLIMATE CHANGE: VOLUME I, 2005-6, at 44, Table 6, *available at* http://www.scribd.com/doc/122554/stern-report-the-economics-of-climate-change. Table 6 assumes a 550 ppm target fir CO2, 3% discount rate, and 20 years at 2005 prices. *Id.*. 550 ppm would not come anywhere near keeping temperatures below 2˚C according to current projections and 3 % is unreasonably low. So this is likely to be very much of a lower bound using projections used at the time of this Lords' report. *Id.*

Appendix 1: Analysis of Two Cases to Determine the Feasibility of Using ERD to Control Dangerous Global Climate Changes

Analysis of Major Parameters

The Rive et al. paper[250] uses a number of factors or parameters (which I have labeled P1, P2, P3, and P5) in determining the feasibility of emissions reductions to meet several alternative temperature limits. In addition there is a need to enhance their analysis by adding an additional parameter (P4) in order to make the analysis correspond better to the real world, where the final outcome of ERD implementation can never be fully known in advance. Instead, it must be based on expectations of future implementation of proposed mitigation measures. It should be noted that this added parameter by itself does not change the conclusions in the two cases examined, although it certainly reinforces them. In order to escape the above conclusions concerning the limited usefulness of ERD in each case, one presumably must believe that ERD meets tests concerning all of the following parameters (see Table 2 below and the sources for it):

(P1) *Climate sensitivity to increased CO_2.* To meet the test of this parameter in Case 3.a it would be necessary to assume that sensitivity is less than about 3.1˚C assuming a 2˚C limit. In other words, reliance on ERD approaches depends critically on the assumed CO_2 sensitivity. Even if one believes that Hansen et al.'s 6˚C is too pessimistic, one must believe that the sensitivity is no more than about 3.1˚C in order to fall within Rive et al's possibilities curve. Hansen et al. clearly believe that the IPCC failed to take into account very significant factors that the IPCC may not have known about at the time since the Hansen et al. paper was not published until almost a year after the IPCC deadline. Just because the majority of the IPCC reviewers held a different view at that time does not make Hansen et al. incorrect, however. In Case 3.b Rive et al.'s analysis assumes that P1 is about 3˚C, so Case 3.b meets this test.[251]

(P2) *Maximum global temperature increase that avoids a substantial risk that there will be a dangerous climate change if global temperatures increase more than that amount.* The higher the maximum, the easier it is to meet it. In Case 3.a, it would be nec-

[250] *See generally* Rive et al., *supra* note 95.
[251] *See generally* Rive et al., *supra* note 95.

essary to believe that ERD could reduce the increase to no more than a further 1°C (1.8°C above pre-industrial levels) to avoid the large increase in sea level predicted by Hansen et al. (2). This is actually significantly more stringent than the requirement of less than 2°C in case 3.b. But since Rive et al did not consider 1.8°C, it will be (charitably) assumed here that meeting the 2°C limit, which they do show, is the equivalent of meeting 1.8. With this assumption, ERD satisfies this test for both cases. (P3) *Relation of case to error bounds defined by Rive et al.* It is assumed here that Rive et al.'s analysis is as valid as is currently possible. Under Case 3.a, in order for the conclusion not to hold, it would be necessary to believe that the results of using a 1.8°C limit with Hansen et al.'s doubled temperature sensitivity to CO_2 falls on or inside the implementation possibilities curve for this temperature limit, which it comes nowhere close to doing.[252] In case 3.b, the average probability estimates do fall on the implementation possibilities curve for a 2°C limit and early "action," so it does qualify.[253]

(P4) *The ratio of actual emissions reductions that would be achieved in the real world application of ERD to the optimized reductions assumed by the modeling studies that Rive et al. used to derive their results.* This is not part of Rive et al.'s analysis but has been added to make the analysis more realistic since this is likely to be a major problem with actually implementing ERD in the manner that may be agreed to.[254] Rive et al. effectively assume that the ERD efforts are as successful in reducing the risk of global warming as the underlying studies they use assume they are, with the exception that they differentiate between "early" and "late" action.[255] Since these studies effectively assume 100 percent success (a ratio of 1), Rive et al. do as well. There is ample reason to believe, however, that the real world implementation of whatever measures may actually be decided on to implement ERD will fall well short of the

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[252] *Id.* at 382 (relying on Figure 6).
[253] *Id.*
[254] See *supra* Section I.D.2.
[256] Rive et al., *supra* note 95, at 378-79.

ideal cases assumed by the underlying studies for a number of practical reasons,[256] taking into account that the Rive et al. analysis will really only be useful before a decision is made as to how to implement climate change control. If, for example, implementation should be carried out through an extension of the Kyoto Protocol, P4 would be the ratio of actual reductions achieved worldwide to the reductions agreed to in the extension worldwide. Although the period of performance of the current Protocol is not yet over, it is already clear that the ratio will be much less than 1.0 when it is completed.[257] The reasons advanced in Section I.D., above, are just a few of the factors that make it hard to believe that P4 would be very large. And there is every reason to believe that it would be quite small. But assuming that experience to date in jurisdictions with relatively advanced energy efficiency programs, such as California and Great Britain, is relevant for determining P4, P4 would currently be roughly 0 since no real decrease in emissions has occurred. Now it is possible that more might be accomplished by a more aggressive ERD effort, such as is now proposed by some, but that is far from clear. It would be particularly necessary to believe that the ratio is very high to change the conclusion in Case 3.b, because it would have to be in order to achieve even the probabilities shown by Rive et al.'s analysis. So it is extremely unlikely that this parameter could be used to change the conclusions with regard to the usefulness of ERD in this Case. (P5) *The cumulative probability as defined by Rive et al.* This is the probability that a given temperature limit will be achieved given the variability in the underlying studies used. An important issue is what the minimum probability society would find acceptable if it were to undertake a serious effort at climate change control and below which it would not want to pursue a particular control approach given the sacrifices involved. In case 3.a, the actual probability shown by Rive et al.'s analysis is 0, which is clearly unacceptable. But in Case 3.b this probability is more crucial since Rive et al. shows that under ideal circumstances there is a 50 percent probability of achieving a 2°C limit.[258] Given

[256] *See supra* Section I.D.2.
[257] Carlin, *Global Climate Change Control*, *supra* note 2, at 1431.
[258] Rive et al., *supra* note 95, at 382 (relying on Figure 6).

the gravity of the possible consequences and the sacrifices involved, I believe that 50 percent is much less than citizens would be willing to accept if carefully polled, but this is a matter of judgment. 90 percent would appear more reasonable, but no "acceptable" number above 50 percent leads to an unchanged conclusion. The conclusions from this analysis are that ERD fails in Case 3.a because four of five parameters fail. In Case 3.b, ERD fails unless a probability of 50 percent is acceptable (in P5) and the achievement ratio (P4) is much higher than it is likely to be. Even so, it would be extremely expensive according to Rive et al.[259]

[1] See *id.* at 385 (relying on Table 1).

Table 2: Analysis of Major Parameters to Determine Feasibility of Using ERD to Control Dangerous Global Climate Changes

Parameters	(P1) Temp. sensitivity (˚C)	(P2) Temp. limit (˚C)	(P3) Relation to Rive sensitivity bounds	(P4) Real world achievement ratio	(P5) Probability of achievement of limit (%)
Case 3.a—Hansen et al. correct on risk of Greenland/West Antarctic ice sheet disintegration if P2>1.8˚C					
A.1. Actual/ assumed	6	1.8	Well outside high estimate	Very low	0
A.2. To accept ERD	≤3.1	≤1.8	Meets average projection	Very high	≥90
A.3. To reject ERD	>3.1	>1.8	Outside high estimate	Medium to low	<90
A.4. Conclusions concerning ERD	Fails	Meets using 2˚C	Not achievable	Fails	Fails
Case 3.b—EU correct that global temperature rise should be no more than 2˚C					
B.1. Actual/ assumed	3	2	Meets average projection	Very low	50
B.2. To accept ERD	≤3.1	≤2.0	Meets average projection	Very high	≥90
B.3. To Reject ERD	>3.1	>2.0	Outside high estimate	Medium to low	<90
B.4. Conclusions concerning ERD	Meets	Meets	Meets	Fails	Meets if 50% acceptable; fails if acceptable P5≥51

Sources for Table 2:

Column P1: Row A.1: Rive et al., *supra* note 95; Rows A.2, A.3, B.2, and B.3: Based on visual reading of Table 6 of Rive et al., *supra* note 95, at 382; Row A.4: Comparison of Row A.3 with A.1; Row B.1: Approximation of IPCC estimate shown in the explanation for Figure 2 of Rive et al., *supra* note 95; Row B.4: Comparison of Rows B.2 and B.1.

Column P2: Rows A.1, A.2, and A.3: Hansen et al., *supra* note 69, 1°C increase over current plus approximation of 0.8°C current over pre-industrial temperatures since this is an optimistic assumption; Row A.4: Comparison of Rows A.3 with A.1. Rive et al., *supra* note 95, analyzes 2°C, but not 1.8°C, so it is assumed (optimistically) that the two are the same for the purposes of this cell; Row B.1: *See* text for explanation of selection of 2.0°C; Rows B.2 and B.3: EU policy ; Row B.4: Comparison of Row B.2 with B.1.

Column P3: Rows A.1, A.2, A.3, B.1, B.2, and B.3: Based on Rive et al., *supra* note 95, Figure 6 using black sensitivity probability lines, 2°C limit, and 2025 peak; Row A.4: Comparison of Row A.3 with A.1; Row B.1: Also based on ACIA, *supra note* 110; Row B.4: Comparison of Rows B.2 and B.1.

Column P4: Rows A.1, A.2, A.3, B.1, B.2, and B.3: *See* discussion concerning column P4 in main text of this paper; Row A.4: Comparison of Row A.3 with A.1; Row B.4: Comparison of Rows B.3 and B.1.

Column P5: Row A.1: Table 1 of Rive et al., *supra* note 95. 1.8 GtCeq is about 80% of year 2000 emissions shown as 9.1 GtCeq in the footnote to Table 1. In this and all their other cases, Rive et al., *supra* note 95, assume that there will be no overshooting because they believe that overshooting might compromise the overall objective. Their term 'overshoot' refers to when a scenario exceeds a given target (i.e., temperature) for a short period of time as a result of climate system inertia, before eventually returning to the target level. Rows A.2, A.3, B.2, and B.3: Estimate as described in text. Row A.4: Comparison of Row A.3 and A.1; Row B.1: ACIA, *supra note* 110. Row B.4: Comparison of Row B.3 and B.1. This conclusion holds as long as B.3 is greater than in Row B.1, regardless of the 90 % estimate used for B.3.

Table 2: Analysis of Major Parameters to Determine Feasibility of Using ERD to Control Dangerous Global Climate Changes .

Parameters	(PI) Temp, sensitivity (°C)	(P2) Temp, limit CO	(P3) Relation to Rive sensitivity bounds	(P4) Real world achievement ratio	(P5) Probability of achievement of limit (%)
Case 3.a—Hansen et al. correct on risk of Greenland/West Antarctic ice sheet disintegration if P2>1.8°C					
A.l. Actual/ assumed	6	1.8	Well outside high estimate	Very low	0
A.2. To accept ERD	<3.1	<1.8	Meets average projection	Very high	>90
A.3. To reject ERD	>3.1	>1.8	Outside high estimate	Medium to low	<90
A.4. Conclusions concerning ERD	Fails	Meets using 2°C	Not achievable	Fails	Fails
Case 3.b—EU correct that global tem		perature rise should be no more than 2°C			
B.I. Actual/ assumed	3	2	Meets average projection	Very low	50
B.2. To accept ERD	<3.1	<2.0	Meets average projection	Very high	>90
B.3. To Reject ERD	>3.1	>2.0	Outside high estimate	Medium to low	<90
B.4. Conclusions concerning ERD	Meets	Meets	Meets	Fails	Meets if 50% acceptable; fails if acceptable P5>51

Sources for Table 2:

Column PI: Row A.1: Rive et al., *supra* note 95; Rows A.2, A.3, B.2, and B.3: Based on visual reading of Table 6 of Rive et al., *supra* note 95, at 382; Row A.4: Comparison of Row A.3 with A.I; Row B.I: Approximation of IPCC estimate shown in the explanation for Figure 2 of Rive et al., *supra* note 95; Row B.4: Comparison of Rows B.2 and B.I.

Column P2: Rows A.1, A.2, and A.3: Hansen et al., *supra* note 69, 1°C increase over current plus approximation of 0.8°C current over pre-industrial temperatures since this is an optimistic assumption; Row A.4: Comparison of Rows A.3 with A.1. Rive et al., *supra* note 95,