Supplementary Material for AWMA Publication of

"Prospects for Future Climate Change and the Reasons for Early Action"

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Introduction

There are three parts to the supplementary material, each prepared to be a stand-alone summary of the particular topic. The three topical areas are:

A. Early Identification of the Effect of Carbon Dioxide on Climate (starting on page 1)

B. The History and Structure of Climate Change Assessments (starting on page 9)

C. An Overview of Approaches to Geoengineering as a Potential Hedging Strategy (starting on page 20)

A. Early Identification of the Effect of Carbon Dioxide on Climate

Recognition of the special challenge posed by the release of carbon dioxide (CO_2) to the atmosphere goes back several centuries. If one burned a tree, the combustion products obviously went into the atmosphere and then were presumably pulled back out as new trees grew to replace the ones cut down. But what happened when one burned coal—was new coal formed at the same rate? And what were these gases and how did the chemical cycling work?

Studies in the early 19th century by French scientist Joseph Fourier identified and explained infrared (IR) radiation. By the mid-19th century, British scientist John Tyndall had determined that CO_2 and methane (CH_4), as well as water vapor, were IR absorbing and emitting gases. Indeed, because of their molecular structure, all gases that have three or more atoms are capable of absorbing infrared radiation. Because particular vibrational and rotational modes can be excited, the absorption occurs in particular spectral bands. Once these modes are excited, the energy is then transferred to the surrounding molecules by collision, warming the air. A similar process works in reverse—higher air temperatures excite the bands, and they emit the radiation as a photon of a characteristic wavelength, transferring the energy to wherever the photon is absorbed.

The First Estimate of CO_2-Induced Climate Change

In 1896, Swedish scientist Svante Arrhenius[1,2] was able to calculate that a doubling of the atmospheric CO_2 concentration would, by changing the characteristic absorption and emission of the atmosphere, warm the world by 5.4 ºC. With this information, Arrhenius and Arvid Högbom then estimated the emissions of CO_2 from industry and projected that the CO_2 concentration could reach double the existing concentration in a few thousand years, thus causing a warming in the very distant future.[2] Scientific questioning of the validity of the hypothesis raised two criticisms:

1. Would not the oceans, which have much more dissolved carbon than the atmosphere, absorb most of the CO_2 emitted into the atmosphere, sharply limiting the rise in concentration?
2. Would not the increasing atmospheric CO_2 concentration saturate the IR absorption bands, very much limiting any future warming influence?

In publications beginning in the 1930s, British engineer Guy Stewart Callendar presented early observations indicating that both the CO_2 concentration and the large-scale average temperature were rising.[3] Although his observations seemed to corroborate the projections of Arrhenius, they were considered unconvincing as a result of their limited number and their proximity to industrial source regions of CO_2. While the idea remained barely alive, it took until the mid-20th century to convincingly address both of these criticisms in ways that made clear that human-induced climate change was a real possibility.

Using radiocarbon dating to determine the age of deep-ocean waters, American scientists Roger Revelle and Hans Seuss[4] provided the observations that countered the first criticism. Their observations, and additional ones that followed, indicated that dissolution of emitted CO_2 into the upper wind-mixed layer of the ocean would be rapid, achieving equilibration within a few years. However, the transport and mixing of carbon from the upper 100-200 m of the ocean to the deep ocean was very slow, taking on the order of a thousand years to achieve a full replacement of deep waters with waters having an elevated CO_2 concentration. As a result, the rate of increase of the atmospheric CO_2 concentration would be mainly determined by the capacity of the atmosphere and upper ocean to hold the extra carbon (somewhat later, the potential for the terrestrial biosphere to take up extra carbon was also accounted for).

Measurements of the CO_2 concentration were begun in 1957 by C. David Keeling.[5,6] His goal was to take precise and continuous observations in relatively clean air rather than to take periodic measurements in many locations. To ensure access to clean air representative of the global concentration, he initiated monitoring atop Mauna Loa in Hawaii and at the South Pole. Over the following few years, his observations demonstrated that, while there was a seasonal signal due to the uptake and release of CO_2 by vegetation, the average annual concentration was indeed rising. Refined estimates of the emissions of CO_2 from fossil-fuel combustion and of the age of the CO_2 using radiocarbon measurements indicated that about half of the emitted CO_2 was remaining in the atmosphere and contributing to the higher CO_2 concentration.

Nearly simultaneously, the earliest computers were being put to work to try to simulate atmospheric behavior and ultimately realize the early vision of Lewis Richardson.[7] Through a long series of algebraic calculations undertaken during breaks from his service as an ambulance driver during World War I, Richardson attempted to use the fundamental physical laws of requiring conservation of mass, momentum, and energy to predict the evolution of European weather over a 6-hour period. Although his calculation failed, advances in numerical techniques, computers, and observations allowed John von Neumann and others to try again beginning in the late 1940s.

Although most attention in the computing efforts was focused on developing horizontally resolved models to use for large-scale weather forecasting,[8] a few scientists began working on simulating the vertical structure and energy balance of the atmosphere, which must be represented in simulations of climate and climate change. The initial simulations led eventually to a classic paper by Syukuro Manabe and Richard Wetherald[9] of the Geophysical Fluid Dynamics Laboratory of what later became NOAA. The paper described results using a one-dimensional (vertical) model of the atmosphere that treated solar and IR radiation as well as, in a simplified manner, the net effects of atmospheric transport, convection and cloud cover. Their simulations of a representative vertical column through the atmosphere indicated that a doubling of the atmospheric CO_2 concentration would lead to a global-average surface warming of roughly 3 ºC if the relative humidity were to remain constant (and less than half this if the atmospheric water vapor concentration was assumed not to increase).

While this estimate of the warming was less than that calculated by Arrhenius,[1] it was significantly more than the value his critics concluded would occur as the CO_2 absorption bands (viewed from the surface) became saturated. With respect to this criticism, the model results indicated that, while an increase in the CO_2 concentration would lead to greater absorption, changes in temperature, water vapor and the concentrations of other species with altitude could not be treated properly in a one-layer representation of the atmosphere. Instead, the atmosphere needed to be considered as a series of layers, each having its own (typically small) absorptivity and emissivity as a result of its concentration of IR absorbing and emitting gases. The situation is roughly equivalent to adding blankets to cover someone lying outside on a cold night—although each blanket might let some heat through (i.e., IR radiation passing through at non-absorbing wavelengths), when the blankets are piled on top of each other, the collective effect is to make it more difficult for IR radiation emitted at the surface to make it up through the atmosphere and escape to space. Because atmospheric convection controls the vertical gradient of temperature (i.e., the lapse rate), for the upper layers of the atmosphere to emit an amount of radiation to space that equals the amount of solar radiation that is absorbed, the surface has to become warmer.

Recognition that Global Warming Was a Matter of Concern

With both of the criticisms of the Arrhenius hypothesis rebutted, and with the accelerating pace of increases in global population and per capita use of fossil energy, the projections that it would take a few thousand years to double the atmospheric CO_2 concentration dropped to roughly a century; at this rate, human activities would be significantly affecting the climate within a few decades. These early results formed the basis for an appendix included in the 1965 report by the

President's Science Advisory Council, which was the first report to high levels of the U.S. Government on this subject. The appendix,[10] prepared by a scientific panel chaired by Revelle, laid out the various aspects of the issue, from the carbon cycle to projected impacts. Although that report over-estimated the pace of progress in climate change modeling and under-estimated the rate of increase in the use of fossil fuels, it otherwise provided a description of the problem that has stood the test of time.

Manabe and Wetherald's[9] finding that the magnitude of the temperature response depended on how atmospheric water vapor concentrations would change led to much closer attention to possible feedback mechanisms. Studies indicate that the most important positive feedback results from increases in the water vapor concentration. If the amount of water vapor in the atmosphere were to stay constant with a temperature increase, then only the increased CO_2 concentration would be enhancing the trapping of IR radiation and contributing to global warming. Were this what would happen, it is estimated that a doubling of the CO_2 concentration would lead to warming of ~1 ºC.

However, observations make clear that warmer latitudes have a higher absolute humidity than colder latitudes, providing an empirical indication that warming will lead to a higher absolute humidity. On average, the relative humidity, which is controlled by the atmosphere's circulation and hydrologic cycle of evaporation and condensation, tends to be more stable, balanced between humid air in cyclonic (low-pressure) regions and dry air in anti-cyclonic (high-pressure) regions.

To mimic the overall stability of the relative humidity in their initial one-dimensional (vertical) model, Manabe and Wetherald[9] assumed that it would remain constant. Later studies, with many types of models that rigorously treat the global hydrological cycle and do not make assumption all suggest that water vapor concentrations will rise as warming occurs, and in an amount quite consistent with the early assumption that the relative humidity would remain constant (Ref. 11, Chapter 7). Thus, what happens is that the initial increment in CO_2-induced warming increases the capability of the atmosphere to hold water vapor (actually, it raises the temperature at which water vapor is removed), and increased evaporation then pushes the water vapor concentration up. This additional water vapor traps additional IR radiation from the surface, radiating some of this energy back to the surface, causing further warming. This increment to warming triggers additional IR radiation to the atmosphere, causing warming that allows additional water vapor and this increases IR trapping, causing further warming. This positive feedback has the effect of nearly tripling the warming effect of the initial increase in the CO_2 concentration.

To better understand latitudinal differences and to quantitatively estimate the effects of the various feedback processes, Budyko[12] and Sellers[13] constructed energy balance models that calculated, in a connected way, the energy balance for each latitude band from pole to pole. These early models, which were one-dimensional in latitude, were used to explore, for example, the amplifying effects of snow and ice albedo feedback. This positive feedback works as follows: warming leads to melting of snow, which reduces the local albedo (reflectivity) of the surface, leading to greater absorption of solar energy, which leads in turn to warming and further melting of snow and ice, starting the cycle again. Further studies identified additional amplifying (positive) and damping (negative) feedbacks, especially relating to changes in cloud amount, height, and optical depth; Schlesinger and Mitchell[14] provide an early review of the understanding of feedback mechanisms.

Although the first global, three-dimensional atmospheric model incorporating water vapor was run in the early 1960s[15], the first global model run in a climate mode (so including ocean heat capacity and the seasonal cycle) was not run until the 1970s.[16,17] Based on the results of these early models and using available information about the Earth's climatic history, a 1979 summer study of the National Research Council chaired by Jules Charney[18] estimated "the most probable global warming for a doubling of CO_2 to be near 3 ºC with a probable error of ± 1.5 ºC." The broad range was intended to allow for the possibility that the sum of feedbacks, particularly from clouds, could either amplify or damp the response derived from the increase in CO_2 and water vapor.

The Developing Observational Record

At the same time as the models were helping to improve theoretical understanding, the early warming identified by Callendar in the observational data reversed,[19] with the Northern Hemisphere undergoing modest cooling during the 1950s and 1960s. One hypothesis for explaining the cooling emerged from the intensifying studies of Earth's climatic history, particularly of the glacial-interglacial cycling that characterized most of the last million years. Reconstructions of changes in temperature derived from painstaking analysis of the varying time history of temperature-sensitive marine organism buried in ocean sediments suggested that glacial cycles had been recurring on roughly a 100,000-year cycle. The periodicity appeared to match changes in the shape (i.e., ellipticity) of the Earth's orbit, with warm interglacial conditions such as the Holocene tending to occur only ~10% of the time.[20] This led some to speculate that the present glacial must be near its end and the onset of the next ice age must be approaching.

An alternative hypothesis was that human activities were sharply increasing the tropospheric loading and cooling influence of sulfate aerosols. By resorting to tall stacks to more widely disperse the increasing emissions of sulfur dioxide (SO_2), their lifetime was being significantly extended. As a result, sulfate aerosols were increasingly being observed around the Northern Hemisphere mid-latitudes. With aerosol concentrations up sharply, there was greatly increased reflection of solar radiation, and so their cooling influence overtook the more slowly accumulating warming influence of increasing GHG concentrations. Both hypotheses drew significant media attention and even headlines that the world was cooling instead of warming.

Suggestions that the cooling would continue, however, quickly lost the low level of support that they had.[21] Because the emitted CO_2 is only slowly transported to the deep ocean, increases in the atmospheric CO_2 concentration will persist for centuries, even as particular molecules of CO_2 are being exchanged between the atmosphere and terrestrial biosphere and atmosphere and surface ocean. By contrast, because of removal by precipitation and dry deposition, the lifetime of sulfate particles in the troposphere is at most two weeks, so the aerosol loading results only from very recent emissions. As a result, over time, the accumulating warming influence of CO_2 will significantly dominate the cooling influence of sulfates.

In addition, because the primary removal process for sulfate aerosols is precipitation, the desire to reduce the health and environmental impacts of acid deposition (i.e., “acid rain”) led to efforts to reduce SO_2 emissions. The reduction in SO_2 emissions has continued until recently, when this trend is likely being reversed by the very rapidly increasing SO_2 emissions from coal-fired power plants in China and India. Given the difference in lifetime, however, there is no way that the ongoing CO_2 emissions will not lead to its warming influence dominating over the long-term.[22.23.24]

Recognition that CO_2 is not the Only Greenhouse Gas

Once understanding developed about how the emissions of CO_2 were leading to higher concentrations, scientists developed instruments and made measurements in search of other greenhouse gases whose concentrations were undergoing rapid change. It quickly became clear that human activities were also increasing the concentrations of CH_4, N_2O, and many halocarbons (particularly chloro-fluorocarbons [CFC]-11 and CFC 12, but also many others).

Model simulations indicated that these additional changes in composition, along with the change in stratospheric ozone (O_3) that were being induced, were significantly augmenting the warming influence of the rising CO_2 concentration.[25] In addition, emissions from human activities were contributing to degradation of air quality, especially because of the emissions of carbon monoxide (CO) and nitrogen oxides (NO_x), which were contributing to an increase in the tropospheric concentration of ozone (O_3).

By IPCC’s Third Assessment Report (IPCC, 2001, Chapter 4), it was clear that there were a very large number of species to be considering. Rather than too briefly treat the influences of urban and regional air pollution on climate and of climate on urban and regional air quality in this review, it was agreed with AWMA that the main focus in this review would be on global climate change and resultant impacts, leaving the air quality aspects to be covered separately. Clearly, however, human-induced perturbations to the concentrations of greenhouse gases (GHGs) other than CO_2 are very important, and will be especially so as the effort is made to limit the combined contribution to warming of all GHGs.

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B. The History and Structure of Climate Change Assessments

Early Assessments of Climate Change

The potential for human activities to affect atmospheric composition and climate moved from being a purely scientific issue to an issue likely to have public policy implications starting in the 1960s. The early observations of the rising carbon dioxide (CO_2) concentration were consistent with the new understanding of the reasons for slow ocean uptake of CO_2. Model simulations made clear that the rising CO_2 concentration would trap additional infrared (IR) radiation, which would warm the Earth even though the spectral bands appeared to become saturated when viewed from the surface. Emissions would be rising as the world developed. While the world was not warming during the 1960s, it did appear it was time to start to regularly pull together the state of understanding about this issue and to inform government leaders about it.

The first assessment of the climate change issue was prepared in 1965 under the auspices of the President's Science Advisory Committee (PSAC). The panel was chaired by Roger Revelle, and included as members Wallace Broecker, Harmon Craig, C. David Keeling, and Joseph Smagorinsky, all prominent scientists in their fields. They summarized their conclusions and findings as follows:[1]

> Through his worldwide industrial civilization, Man is unwittingly conducting a vast geophysical experiment. Within a few generations he is burning the fossil fuels that slowly accumulated in the earth over the past 500 million years. The CO_2 produced by this combustion is being injected into the atmosphere; about half of it remains there. The estimated recoverable reserves of fossil fuels are sufficient to produce nearly a 200% increase in the carbon content of the atmosphere.
>
> By the year 2000 the increase in atmospheric CO_2 will be close to 25%. This may be sufficient to produce measurable and perhaps marked changes in climate, and will almost certainly cause significant changes in the temperature and other properties of the stratosphere. At present it is impossible to predict these effects quantitatively, but recent advances in mathematical modeling of the atmosphere, using large computers, may allow useful predictions within the next 2 or 3 years.

In reality, the CO_2 concentration went from about 320 ppmv in 1964 to about 370 ppmv in 2000, so an increase of just over 15% (their projected range was actually 14-30%, and the year 2000 concentration is about 32% above its preindustrial level). Climatic effects were being noticed by the year 2000. Progress on modeling, however, was not as rapid as was projected.

The PSAC panel also recommended an enhancement of the research programs on climate change, eventually leading to dedicated research programs and further integrated evaluations. A report by the National Academy of Sciences[2] in 1975 provided an overview about what was known about past changes in climate. Workshops over the next several years sponsored by the Department of Energy[3,4] looked at the science of climate change and potential impacts. Some very cold winters during the 1970s led to Congressional hearings, including early testimony that I contributed,[5] and the establishment of research programs by a number of agencies, especially including DOE, NASA, NOAA, and NSF. In the 1980s, major overview reports by the National

Research Council[6] and Department of Energy[7,8,9,10] made clear that the hypothesis that rising concentrations of greenhouse gases (GHGs) would change the climate was solidly underpinned by the science. As a result, research programs were further increased.

The climate change issue also gained international attention, again beginning with reports of expert panels. The *Study of Critical Environmental Problems*[11] and *Study of Man's Impact on the Climate*[12] came to similar conclusions as PSAC.[1] Their recommendations laid the framework for what eventually became the World Climate Research Programme (WCRP), which was approved at the First World Climate Conference in 1979. Eventually, progress in understanding led to the convening of a major conference in Villach, Austria in 1985 that brought together the scientific and governmental communities to consider next steps. The key conclusions and recommendations of that conference[13] were:

1. Many important economic and social decisions are being made today on long-term projects--major water resource management activities such as irrigation and hydro-power, drought relief, agricultural land use, structural designs and coastal engineering projects, and energy planning--all based on the assumption that past climatic data, without modification, are a reliable guide to the future. This is no longer a good assumption since the increasing concentrations of greenhouse gases are expected to cause a significant warming of the global climate in the next century. It is a matter of urgency to refine estimates of future climate conditions to improve these decisions.
2. Climate change and sea level rises due to greenhouse gases are closely linked with other major environmental issues, such as acid deposition and threats to the Earth's ozone shield, mostly due to changes in the composition of the atmosphere by man's activities. Reduction of coal and oil use and energy conservation undertaken to reduce acid deposition will also reduce emissions of greenhouse gases; a reduction in the release of chloro-fluorocarbons (CFCs) will help protect the ozone layer and will also slow the rate of climate change.
3. While some warming of climate now appears inevitable due to past actions [i.e., to both past emissions and the failure to adopt policies to limit them], the rate and degree of future warming could be profoundly affected by governmental policies on energy conservation, use of fossil fuels, and the emission of some greenhouse gases.

These findings, which are even more clearly supported today, prompted many countries to initiate assessments of what climate change would mean for them. The call for such studies even made it into an official summit communiqué from U.S. President Reagan and Soviet Premier Gorbachev, leading to a joint report on the prospects for future climate.[14]

Formation of the Intergovernmental Panel on Climate Change (IPCC)

A clear message from the scientific studies was that understanding and dealing with the climate change issue needed to be international. National studies could be of use for adaptation, but building the scientific basis for actions to limit future change would need to be international. To generate such a broad-based consensus, the Intergovernmental Panel on Climate Change (IPCC) was organized as a scientifically focused intergovernmental body in 1988 under the sponsorship of the World Meteorological Organization (WMO) and United National Environment

Programme (UNEP). The members of the IPCC are the governments of the world (and note it is governments that are the official members) that participate in WMO and UNEP, and typically about 150 of the governments have participated.

IPCC's purpose[15] is to provide objective and authoritative scientific information regarding climate change for decision makers at national and international levels. Its work is carried out by preparing periodic, expert assessments summarizing scientific understanding and uncertainties regarding climate change, its impacts on society and the environment, the potential to adapt to climate change, and options for limiting change in the future. While IPCC is an intergovernmental body, government participation mainly occurs at plenary sessions of the IPCC, where decisions are made about the plans for, policies governing, and acceptance and adoption of the reports making up each of the periodic scientific assessments that IPCC sponsors.

To manage IPCC's efforts, the governments elect a set of their representatives to IPCC's Bureau, which proposes and implements the plans for each assessment. For each of the major assessments (completed in 1990,[16,17,18] 1995,[19,20,21] 2001,[22,23,24,25] and 2007[26,27,28,29]), three working groups (WGs) have been organized, covering (in slightly different ways over the years) the science of climate change, the resulting impacts on the environment and society, and the potential for adaptation (i.e., actions that would reduce vulnerability and detrimental consequences), and mitigation (i.e., actions that would limit the activities that are causing climate change).

Nations nominate prominent scientists and other experts to lead and serve on the various WGs, and the IPCC Bureau selects the WG co-chairs from the set of nominations. Each WG has two co-chairs, one from a developed and one from a developing nation. The government of the developed nation co-chair is responsible for funding the establishment and operation of a Technical Support Unit to coordinate preparation of the assessments.

The intense and exacting work of preparing each of IPCC's major assessments and special reports is done by international teams of scientific and technical experts. Based on a chapter plan for each WG's contribution to the overall assessment, convening lead authors, lead authors, and review editors are selected from nominations by the IPCC member governments to undertake the preparation, review, revision and completion of each of the WG's chapters. As part of the process of surveying each field, invitations to submit information are generally issued to the broader scientific community, a step that often brings additional scientists into the process as contributing authors. As a result, many hundreds of scientific, technical, and other experts from universities, industry, government, and public interest groups are brought into the authorship process, and even more are involved as expert reviewers.

The IPCC is not a research organization. While integration and analysis do take place, this is done mainly in the effort to examine, reconcile, and interface the results and findings of different scientific studies that have been published in the expert peer-reviewed literature available worldwide. Guidance to the authors and the multi-stage peer review process is designed to ensure that the IPCC reports are comprehensive and objective, are prepared in an open and transparent manner, and, while being policy relevant, are policy neutral (i.e., the comparative effectiveness of various policy approaches can be evaluated; a particular policy would not be recommended).

Each chapter’s purpose is to summarize and explain what is understood and the degree to which this is the case, encompassing the full range of views represented in the expert literature. The end result is intended to be a critical review that neither excludes viable hypotheses nor necessarily includes inconsistent or poorly supported explanations. That the judgments made in accomplishing this are done fairly and openly is evaluated through an extensive peer-review process. This process is watched over by review editors that report separately up to the national representatives for each WG.

The periodic assessments have led to four products, each directed to a particular audience and so prepared at a different technical level and depth. These four parts are:

1. Chapters: Each WG report is made up of 10-20 chapters, each of which focuses on a particular topic (e.g., observed changes in the cryosphere, impacts on Africa, mitigation options for industry). The primary audiences of the chapters are the scientific experts in the particular field. With this in mind, the technical level is quite detailed; typically, each chapter is 30 to 100 pages long, in fine print, and the chapters are highly referenced. Treatment of uncertainty is typically representative of the approach used in that field (so statements are often carefully hedged, not closing off even quite low probability interpretations). The review process for chapters is very extensive, involving consideration by both independent scientific experts and experts identified by governments. Review editors have responsibility for ensuring that the review comments, which are extensive, are fairly considered and their disposition recorded (and the comments and response are made publicly available). In the IPCC plenary sessions, the governments vote to accept or reject each chapter based on their evaluation of the authors having fulfilled the requirements of summarizing the field and successfully dealing with comments raised during the review process. In the end, each chapter, as a scientific document, is considered the responsibility of its lead authors—agreement on every word and finding is not asked or expected of the IPCC member governments or even of authors of other chapters—these are scientific reviews.
2. Technical Summary (TS) for each WG: Prepared collectively by the convening lead authors for each of a WG’s chapters, the TS is a technical and scientific overview of the entire WG report. The intended audience is the broad scientific and expert community, so the TS has a technical tone and uses traditional approaches to describing uncertainties. Like the chapters, the drafts of the TS are subject to review and revision. Final versions tend to be 50-70 pages long. Again, the government representatives vote in plenary on the acceptance of the TS, not to approve every word or sentence. The result is an authored scientific document.
3. Summary for Policy Makers (SPM) for each WG: SPMs are drafted by a subset of the convening lead authors of each WG, often working with the government representatives serving on the WG’s Bureau. The SPMs are intended to convey and effectively communicate the *highlights* and *significance* of the scientific findings to public and private decision makers—they are not just shorter technical summaries. The SPMs are cross-referenced to the chapters, but use language appropriate to the relative-likelihood decision framework that is typically invoked in making public and private sector

decisions regarding policy, resources and investments.[30,31] The SPMs are each 10-20 pages long, including a number of figures. They are reviewed and revised and then ultimately approved by the representatives of the IPCC member nations on a sentence-by-sentence (sometimes even word-by-word) basis at the plenary sessions, indeed fulfilling their commitment to be "working" groups. There is often extensive negotiation to ensure that the phrasing is both scientifically accurate and understandable and meaningful to the decision makers that are the main audience for the SPMs. While some argue that the negotiation process results in some of the findings being influenced by the political views of particular countries, the overall process has led to texts for SPMs that the scientific representatives consider valid and that have consistently gained *unanimous* approval by the IPCC's national representatives. Given that the process involves so much review, oversight and negotiation, however, statements of findings necessarily tend to be cautiously phrased, lagging behind cutting edge scientific results and likely to somewhat understate the pace and seriousness of change.

4. Synthesis Report (SR): To further facilitate communication with decision makers, the SR presents answers to a small number of cross-cutting questions put forth by the government representatives negotiating agreements under the UN Framework Convention on Climate Change (UNFCCC). [The UNFCCC was negotiated and opened for signature at the Earth Summit in Rio de Janeiro in 1992 and went into force in 1994 after being ratified by virtually all nations.] The SR is drafted by lead authors from each WG and then revised in response to extensive review. Like the SPM, the framing is in terms of relative likelihood of a finding or outcome, with cross-referencing to the chapters providing a linkage to a fuller discussion of the degree of understanding and uncertainty. The executive summary of the most recent SR, which the plenary approves on a word-by-word basis, was about 23 pages long, with supporting material about twice as long.[29]

While the periodic assessment reports of the IPCC are their major product, special updates[32,33] and special reports have also been prepared. Titles of special reports on particular topics include:

- *The Regional Impacts of Climate Change: An Assessment of Vulnerability*;[34]
- *Aviation and the Global Atmosphere*;[35]
- *Emission Scenarios*;[36]
- *Climate Change and Its Linkages with Development, Equity, and Sustainability*;[37]
- *Land Use, Land-Use Change, and Forestry*;[38]
- *Methodological and Technological Issues in Technology Transfer*;[39]
- *Carbon Dioxide Capture and Storage*;[40] and
- *Safeguarding the Ozone Layer and the Global Climate System.*[41]

As indicated by their titles, these special reports have often been done in cooperation with other international groups in order to address topics of joint interest and interlocking impacts.

The IPCC has also prepared technical papers. These papers have focused on such topics as climate change and biodiversity, an introduction to simple models, etc. In addition, supporting materials have been assembled to describe the results of a number of expert meetings and workshops. The four major assessments and the other types of reports are on the Web[15] and from

Cambridge University Press, which has published most of the IPCC reports.

That the reports are developed through an international process and have drawn so extensively from the international scientific and expert community has given them considerable credibility. Many national academies of science and professional organizations have recognized the authoritativeness of the IPCC products and endorsed their findings.

In addition, the media have given the results of the reports extensive coverage, although often focusing on only the most serious of the consequences and omitting important caveats given in various levels of the reports. As a means of trying to convey authority and credibility, the media seldom describe the nature of the process, but instead cite the total number of experts involved in the whole process. This focus on numbers has been unfortunate and confusing to the public, sometimes even generating competing lists of those (in many cases non-experts) said to disagree with the IPCC—science, however, is not decided by vote, but by evidence, analysis, and understanding.

For this reason, the most important phase of IPCC's assessment process is the multi-tiered review. This process will only be credible if it seeks out potentially critical viewpoints—it simply would not be effective if it did not seek out views from those who say they disagree so that the points can be addressed, if not acceded to. Thus, the real authority of the IPCC assessments is not the number of those involved, but the strength of the evidence and analyses after it has been tempered by a rigorous review process. Using these criteria, IPCC has no peer—and most certainly not cleverly named groups such as the Nongovernmental International Panel on Climate Change,[42] which deserve little credibility because their author selection process is intentionally narrow (authors have to disagree with the IPCC conclusions) and the review process, if it exists, is neither broad nor comprehensive.

Having an authoritative scientific evaluation, however, has not been sufficient; equally important is the requirement to communicate the results in a meaningful way. To facilitate this effort, IPCC has most recently been using a two-axis lexicon that separately describes the degree of confidence in the results.[31] In one dimension, the IPCC presents the relative likelihood of the expected result, based on insights drawn from, as available, theoretical and empirical analyses, experiments, experience, model simulations, ensemble analysis, analogs from the past, physical intuition of experts, and other means. Although judgment must, for many aspects of the problem, serve in lieu of strict quantitative probabilistic analysis, attempts are made to indicate the likelihood of various outcomes by associating the following probabilities with more familiar common language terms:

▪ Virtually certain	>99% probability
▪ Very likely	>90% probability
▪ Likely	>66% probability
▪ Medium likelihood	33-66% probability
▪ Unlikely	<33% probability
▪ Very unlikely	<10% probability
▪ Exceptionally unlikely	<1% probability

Recognizing that the likelihood dimension does not differentiate between findings that are weakly or strongly established, the second dimension of the IPCC lexicon indicates the level of confidence that can be assigned to a conclusion, based generally on the consistency across different lines of evidence. To express this dimension, the IPCC uses the following terms:

Very high confidence	At least 9 out of 10 chance
High confidence	About 8 out of 10 chance
Medium confidence	About 5 out of 10 chance
Low Confidence	About 2 out of 10 chance
Very low confidence	Less than 1 out of 10 chance

Conclusion

Because of the level of detail and review in its preparation and the thoroughness of its approval process, IPCC's findings merit significant respect. In my view, those suggesting its findings are overstated or not sufficiently supported deserve little attention, except to the extent that they offer strongly reasoned and highly peer-reviewed alternative explanations and criticisms.

The IPCC's effective and successful completion of each of its assessments led the Nobel Peace Prize committee to name IPCC as co-awardee of the 2007 Nobel Peace Price with former Vice President Al Gore, who has been so instrumental in raising public awareness of the issue over the past several decades. I was among those invited to attend the very moving award ceremony[43], pleased that both scientific discovery and communication of the science were being recognized—neither alone would be adequate for addressing the great challenge of climate change.

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C. An Overview of Approaches to Geoengineering as a Potential Hedging Strategy

“Geoengineering” has come to mean the taking of actions solely for the purpose of controlling the Earth’s climate and/or atmospheric composition. In that there is both expense and risk involved, geoengineering is currently being put forth as, quite possibly, an easier and less expensive approach than changing of energy technologies to counter-balancing the warming influences caused by the ongoing release of greenhouse gases (GHG) to the atmosphere. Basically, the question to be explored is, if human activities can inadvertently cause changes in the climate, are there not advertent approaches that could cancel out these changes so that the great effort of completely reworking the global energy system can be put off or not done at all. Being able to accomplish this would enable society to continue to rely on fossil fuels, especially the abundant resources of coal and unconventional sources of oil.

The most obvious approach to creating cooling that would counterbalance the GHG-induced warming would be to reduce the amount of incoming solar radiation. The first suggestions about how to do this were put forth several decades ago. The initial idea was to create, in effect, a human volcano by injecting sulfate aerosols or their precursors into the stratosphere. As warming started becoming more evident, increasing attention was given to evaluating the emerging set of ideas about how to do this.[1,2,3,4,5]

While some of the approaches look conceptually feasible at reasonable cost, a number of possible environmental impacts have been identified. In addition, it was noted that continued reliance on geoengineering would impose an ongoing obligation on many future generations, introducing significant moral issues into the discussion. With no funding provided for research on the scientific, technical, or social aspects, however, interest in geoengineering receded into the background in the late 1990s as hope emerged that the Kyoto Protocol and later agreements could bring emissions down.

Interest in the possibility of geoengineering did not disappear, however. In response to President Bush including geoengineering on his initial listing of ideas to explore as part of his Climate Change Technology Initiative (CCTI) in 2001, the U.S. Department of Energy convened a workshop on the subject.[6] Plans for a research program were discussed, but in the end, geoengineering was removed from the CCTI set of activities. Although some new ideas did emerge, the draft report was never completed and released. One reason not to pursue geoengineering research that was discussed at the workshop was that, if such approaches are proven viable, they could reduce the incentive to reduce emissions, thus increasing the obligation to pursue geoengineering through many future generations. A more politically related reason for not further pursuit of geoengineering might have been that seriously pursuing geoengineering research would be an implicit acknowledgement that the global warming problem is very serious and that the mitigation steps being taken are inadequate to address it.

With completion of the Kyoto Protocol negotiations in 2001, with its limited emissions reduction goal, and with its implementation not starting until 2005, the acceleration in the atmospheric accumulation of greenhouse gases led to new consideration of a possible role for geoengineering. Paul Crutzen, Nobel laureate for his identification of the potential for stratospheric ozone depletion, was first to propose that geoengineering needed to be seriously considered and that research on how best to do this should be started.[7] His call for moving forward led to several commentaries,[8,9,10] reigniting intensive discussion of the topic[11], and leading to a slowly increasing set of studies evaluating various of the proposed approaches.

Energetically, a doubling of the carbon dioxide (CO_2) concentration leads to a net radiative forcing (RF) of ~3.6 W/m^2 at the tropopause. Countering this warming influence is roughly equivalent, after accounting for the Earth's albedo, to a reduction of incoming solar radiation by 1.9%. This change in flux has served as the reference case for consideration in a number of studies, even though, in order to keep things in balance, the geoengineered counterbalancing would need to be gradually ratcheted up as the CO_2 concentration increased.

While the total energy derived from solar (i.e., visible) and IR radiation may be equal and opposite and should mean the atmosphere will respond in an equal and opposite manner, the seasonal, latitudinal and vertical changes in energy due to changes in solar radiation and GHGs are quite different. For example, solar radiation is concentrated in low latitudes and has strong seasonal and latitudinal gradients; the change in IR radiation is much more evenly spread across latitude and season.

Despite the difference in the geographic and seasonal patterns of the forcing, model simulations indicate that the seasonal and latitudinal responses for temperature change appear to be close to equal and opposite, which is consistent with results from a wide range of scientific studies that have led IPCC to conclude that the change in global average temperature is closely proportional to the global average change in RF. This finding is somewhat surprising, however, in that Earth system history indicates that glacial-interglacial cycling, which represents the largest variation in the climate of the Earth, appears to occur in response to orbital forcing that has no net annual change in global insolation. The reasons for this perplexing result, and it may be unique to colder periods, may relate to the magnitude and persistence of the seasonal and latitudinal changes and the predominance of continental areas and mountains in the Northern Hemisphere where the high albedo of an increase in snow cover can have a very significant effect in initiating glaciation by helping mountain glacier persist and grow into ice sheets.

For geoengineering to proceed and be effective, resolving this apparent paradox would seem to be important. Apparently, it is the heat capacity of the oceans and the adjustment of atmospheric and oceanic circulations that tends to ameliorate the effects of the latitudinal and seasonal differences in the net energy flux at the tropopause on surface temperature.[12] This balancing is not the case, however, for precipitation,[13,14] so very careful analyses will be needed to establish net consequences.

As to actually implementing the reduction in absorbed solar radiation, there are essentially five altitudes of intervention that have been proposed,[1,15] each with its advantages and disadvantages:

1. *First Lagrange point:* The idea is to locate an object to reduce the energy reaching the Earth at the first Lagrange point, which is located ~1.6 million kilometers toward the Sun. Because objects at this point experience about equal gravitational pull by the Earth and the Sun, relatively little energy is required to keep an object at this location. Early[16]

proposed locating a large Fresnel lens at this point to deflect the appropriate amount of solar radiation from its path to the Earth. Such a lens would need to be about 1500 km in diameter; to most cost effectively construct and put in place such a lens, he recommended it be manufactured and lofted from the Moon (thus setting up very large initial costs). One would not notice such a disk from Earth, as it would appear to be within the solar disk. As a result, its associated environmental impacts (except for not alleviating ocean acidification from the ongoing CO_2 increase) would likely be small.

To avoid the need and cost of going to the Moon, Angel[17] proposed using an electromagnetic launch system to carry trillions of very thin deflectors directly from Earth to the first Lagrange point. Each payload would carry nearly a million "sunshades," each almost a meter in diameter. To help maintain their position once they were deployed, each of these deflectors would have an onboard capability allowing them to sail on the solar wind. While cost remains an issue, this approach would allow incremental implementation and have, other than the environmental impacts of the launch process, very minor inadvertent consequences (though again, the atmospheric CO_2 concentration would not be reduced).

2. *Near-Earth orbit:* Because the solar deflectors would be in orbit, the number and size of mirrors needed would have to cover an area of the Earth equivalent to the reduction in solar radiation wanted. For example, reducing solar radiation by 1% (so equivalent to offsetting the equivalent of an increase in the CO_2 concentration of ~150-200 ppmv) would require having about 55,000 mirrors in orbit, each having an area equivalent to a square 10 km on a side[2]. In addition to the very challenging navigational issues and very significant launch requirements, such mirrors would be constantly moving across the face of the Sun, causing frequent, but brief, eclipses. Lofting to only Earth orbit would, however, be less expensive than lifting to the first Lagrange point, and implementation could be incremental and easily reversed.
3. *Stratosphere:* Volcanic eruptions frequently inject materials into the stratosphere, providing insight into how particles can increase the Earth's albedo. The lifetime and circulation of volcanic aerosols in the stratosphere indicate that several million tons of SO_2 per year would need to be injected to counterbalance the warming effects of increasing GHG emissions. Injection of the required SO_2 could be done using, for example, artillery shells, aircraft, or even pipes held aloft by balloons, although many questions remain about details concerning the optimal height of injection, latitude, spatial uniformity, evenness of the distribution needed, effects on precipitation, etc.[15] Because the lifetime of aerosols in the stratosphere is a couple of years, the amount of SO_2 emitted only needs to be of order 5% of present near-surface emissions, so, after the aerosols eventually exit the stratosphere, there would only be a small increment, unless highly localized, to the existing problem of acid deposition.

Like volcanic aerosols, these aerosols would forward-scatter much more light than they would reflect to space, thus creating a hazy sky with very colorful sunrises and sunsets, but substantially reducing the strength of the direct beam needed for mirror-based solar energy technologies (the reduction in the direct solar beam is ~10 times as great as the amount of solar radiation reflected to space). It seems likely, though it is contentious, that these stratospheric particles would intensify ozone depletion, as is the case for volcanic aerosols, thus allowing increased UV radiation through to the surface, with concomitant health and ecological impacts. To reduce the scattering caused by sulfate aerosols, suggestions have been made to use other types of particles or even small balloons, but no ideal approach has emerged.

A variant of this approach that I proposed at the DOE 2001 workshop[6] would be to concentrate deployment of the aerosols in the Arctic lower stratosphere. Because the Sun is only up half the year, the aerosols would only need to be present during the Arctic summer (when daily solar radiation is nearly as much as at the equator). Injected at a low enough altitude, the particles would be removed within 6 months and would, therefore, not be present during the Arctic spring when they might induce significant depletion of stratospheric ozone. In addition, the population north of the Arctic Circle is pretty small, the region already experiences low light levels, and solar energy systems are unlikely to be located there; as a result, the unintended consequences of global aerosol coverage are likely to be modest.

While counterbalancing the GHG effect at these latitudes would require a substantial amount of aerosols, calculations by Caldeira et al.[18] suggest that there would be a number of benefits in addition to limiting the cooling:

- Lowered temperatures would allow reformation of the sea ice, the increased albedo of which would help to limit the warming;
- Limiting the amplified cooling of the Arctic would help to cool the mid-latitudes and generate the cold air masses that are important to creating and sustaining the normal weather of the mid-latitudes;
- Although the temperature drops, precipitation remains high because the water vapor is coming from the still warmed lower latitudes;
- The increased precipitation would fall mostly as snow, helping to build up glaciers and ice sheets, thus helping to limit sea level rise; and
- By generating cold and highly saline waters, enhanced sea ice formation would likely help to sustain the global ocean overturning circulation and its role in transporting CO_2 to the deep ocean and nutrients to the surface.

As to potential adverse impacts, simulations by Robock et al.[14] suggest that the aerosols might not be constrained in the Arctic by the stratospheric circulation that is present. As a result, a larger injection of aerosols would be needed and the spreading aerosols would lead to a reduction in summer convective rainfall extending down into the mid-latitudes. Whether other types of particles or balloons and selective timing and spacing of injection sites might be able to counter the possible adverse impacts has yet to be explored.

4. *Troposphere*: By emitting SO_2 from coal-fired power plants and creating the whitish haze that extends thousands of kilometers downwind from industrialized areas,[19] human activities are already exerting a global cooling influence, perhaps by as much as 1ºC as a result of direct reflection and increase in cloud reflectivity. Because the lifetime of these sulfate particles in the atmosphere is only ~10 days, doubling or tripling this effect would require emitting many tens of millions of tons of SO_2 above current amounts. Such a high injection amount would exacerbate problems of acid deposition, visibility impairment, and human health effects from breathing small particles. However, given the importance of the counterbalancing cooling influence of present emission, sustaining the current level of SO_2 emissions as the CO_2 emissions are reduced might be worth the health and visibility impairment in order to limit peak warming, especially if the sulfates are concentrated above the boundary layer and over the oceans.

An alternative approach to increasing tropospheric reflectivity has been suggested by Salter and Latham,[20] who have proposed launching a fleet of large, interestingly designed, self-propelled sailing ships that traverse relatively pollution free, but cloud-covered regions of the global ocean. Each ship would spray seawater up into the atmosphere through its masts, the intent being that the wind would carry the resulting salt particles into the low-level clouds. By increasing the number of small particles on which water vapor can condense, the albedo of marine stratus clouds would be increased in a manner similar to the creation of contrail-like features by the exhausts of present day steam ships. It is estimated that it would require the launching and ongoing operation of up to a few dozen ships per year, each the size of an old-time clipper ship, to counterbalance each year's emissions. Early simulations suggest that this could indeed have a modest effect.[21]

5. *Surface*: There are a number of ideas about how to brighten the surface.[22] They range from whitening cities,[23] which would help to reduce energy demand, to deploying surface reflectors over the oceans or over deserts. The surface area required to reflect enough radiation back to space to really counterbalance global warming, however, is very large, indeed is much larger than required for reflectors aloft. This is because surface reflection would be effective only in clear-sky areas. In addition, the effects of surface reflectors are limited by tropospheric absorption of solar radiation, and because the surface albedo is already often elevated in clear-sky areas (e.g., in arid environments), so it is difficult to substantially increase the reflected energy. Gaining access to the very large areas of land needed would also increase competition with other uses of the land.

   Shifting to a strategy of increasing ocean surface albedo would provide a greater increment in reflectivity and reduce competition for use of the area. However, rough estimates indicate that one would have to create the equivalent of a Styrofoam continent floating on the Pacific Ocean, and such a structure would likely have adverse impacts on precipitation, the weather, and marine life.

While there do appear to be opportunities, and the costs and associated environmental impacts may well be less than the impacts from increasing greenhouse gas concentrations that they would offset, management of solar radiation would not help with the increasingly damaging effects of ocean acidification, and pursuing such approaches would impose an obligation to continue the geoengineering approach for many decades, if not indefinitely.

An emerging view is that research on geoengineering should be undertaken so that the knowledge is available to take action if global warming significantly accelerates or an important impact threshold is crossed. While the technical and scientific aspects of the research will be daunting enough, it is becoming increasingly recognized that research on how such an effort might ever be presented in a way that would gain international acceptance and how the effort might be successfully and multi-laterally implemented and governed will be equally as challenging.[24]

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